Table of Contents - PSD

8. Planetary Science Division (PSD)

8.a. Demographics

8.a.i. Principal Investigators (PIs)

8.a.i.1. Limitations of the Data – PSD PIs

26,043 submitted proposals are included in the ROSES 2016-2021 database. Please see Appendix Table 1 to see which programs are included. The total number of proposals submitted and selected for each ROSES year and the total number of proposals submitted to each SMD Division cannot be reported due to the Office of the Chief Scientist's suppression guidelines. See *Yearbook Introduction Section 1.a.ii.1 Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics* for more information. The number of proposals rounded to the nearest hundred are included for these two circumstances to provide context. For the Planetary Science Division, there are ~8,200 submitted proposals over all ROSES years: ~7,300 for ROSES 2016-2020 and ~900 for ROSES 2021.

Proposals with PIs who took the survey but selected "prefer not to answer" for all demographic survey questions:

- Submitted proposals: PSD 2016 - 2020: 11% | PSD 2021: 9%
- Selected proposals: PSD 2016 - 2020: 10% | PSD 2021: 10%

Unique identifiers in the dataset are not completely unique. Less than 1% of PIs of submitted ROSES 2016-2021 proposals have more than 1 unique ID in the NSPIRES system.

8.a.i.2. Gender – PSD PIs

PSD PIs: Submitted Gender - Plot

PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated.

Suppressed categories: Non M/F gender (All years).
See *Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics* for more information.

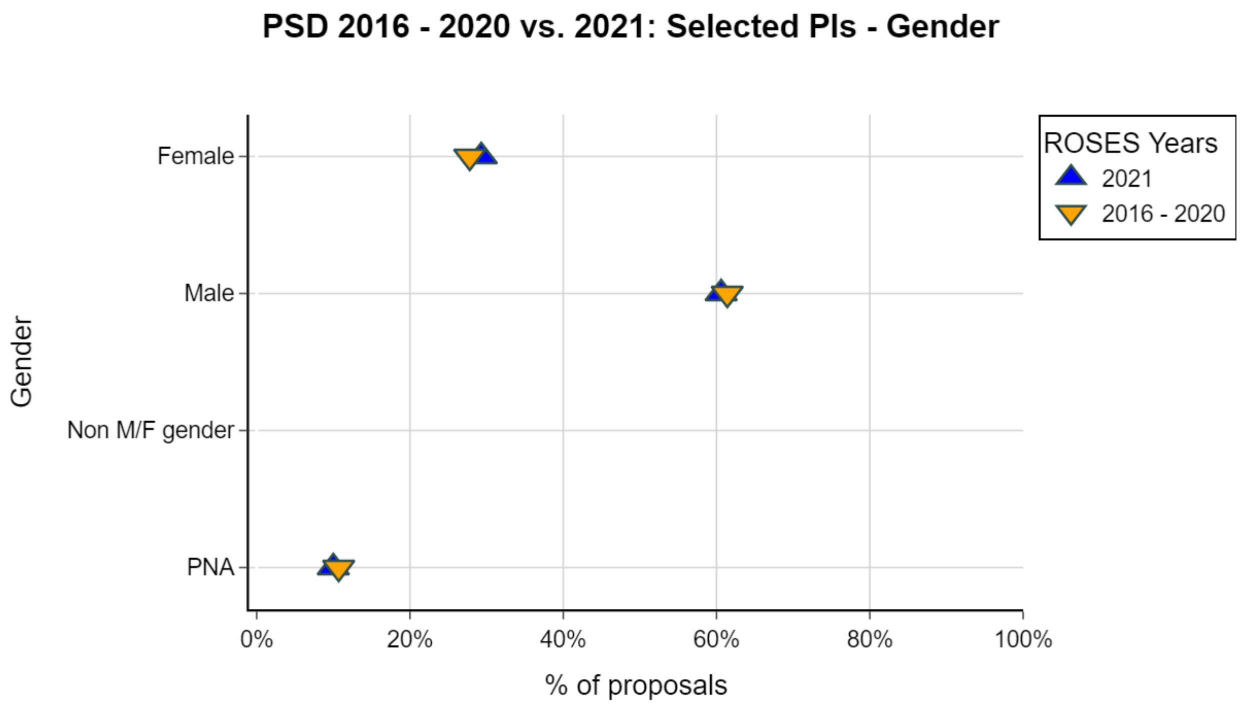
PSD PIs: Submitted Gender - Data Table

PSD 2016 - 2020 vs. 2021: Submitted PIs - Gender

Gender	PSD 2016 - 2020	PSD 2021
Female	25%	29%
Male	63%	62%
Non M/F gender	NR	NR
PNA	12%	9%

PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

PSD PIs: Selected Gender - Plot



PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated.

Suppressed categories: Non M/F gender (All years).
See *Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics* for more information.

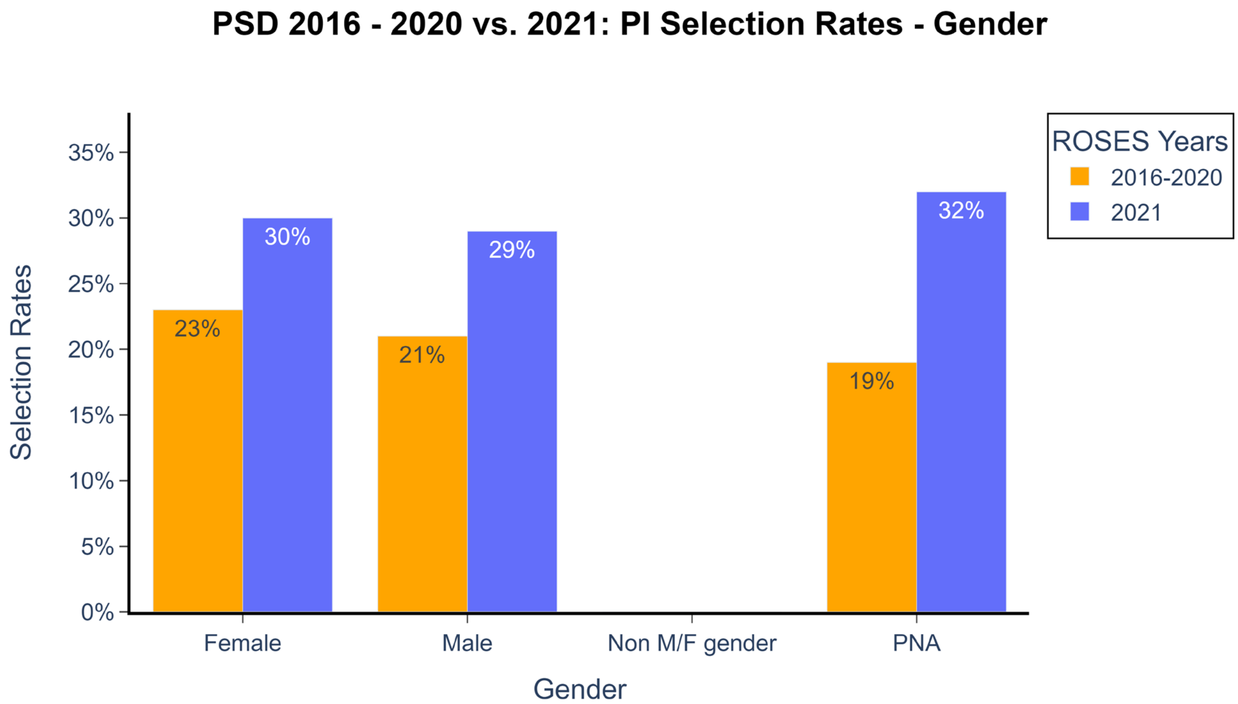
PSD PIs: Selected Gender - Data Table

PSD 2016 - 2020 vs. 2021: Selected PIs - Gender

Gender	PSD 2016 - 2020	PSD 2021
Female	28%	29%
Male	61%	61%
Non M/F gender	NR	NR
PNA	11%	10%

PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

PSD PIs: Gender Selection Rate - Bar Plot



PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated. | Selection rate = # of selected proposals with PIs from a demographic response group/ # of submitted proposals with PIs from the same demographic response group

Suppressed categories: Non M/F gender (All years).
See *Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics* for more information.

PSD PIs: Gender Selection Rate - Data Table

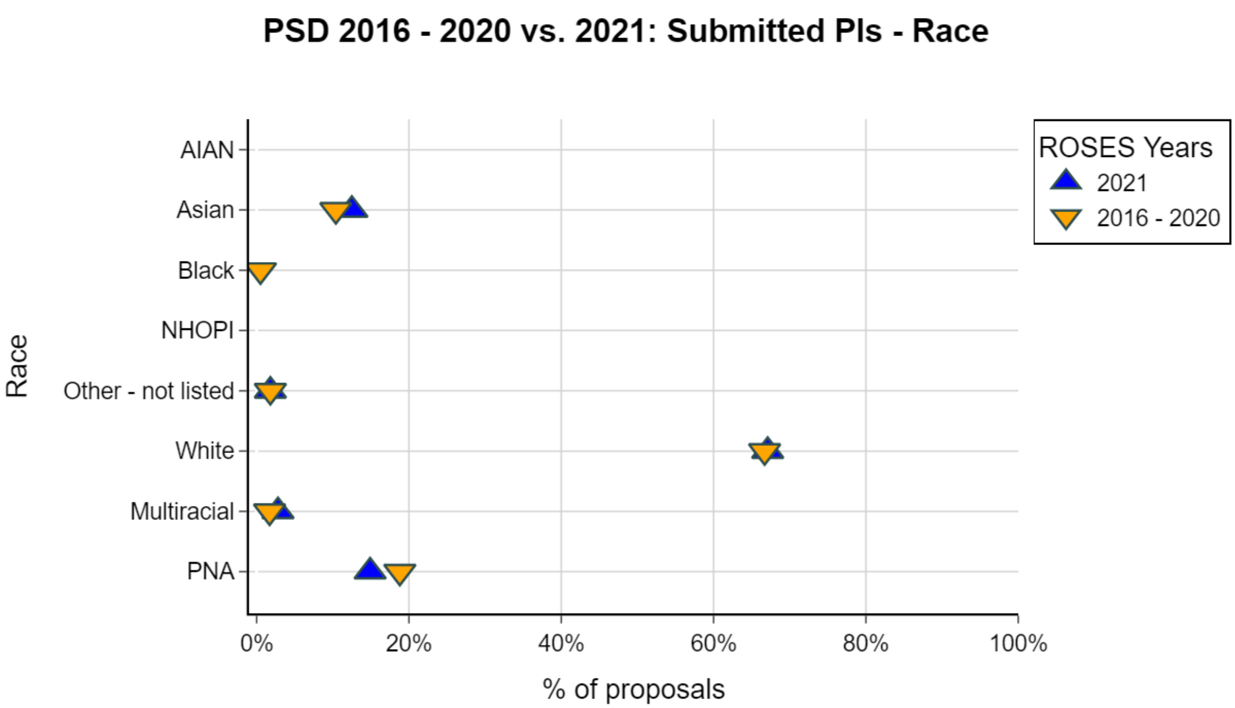
PSD 2016 - 2020 vs. 2021: PI Selection Rates - Gender

Gender	PSD 2016-2020	PSD 2016-2020 Response/All Genders	PSD 2021	PSD 2021 Response/All Genders
Female	23%	1.1	30%	1.03
Male	21%	1	29%	1
Non M/F gender	NR	NR	NR	NR
PNA	19%	0.9	32%	1.1
All Genders	21%	1	29%	1

PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated. | Selection rate = # of selected proposals with PIs from a demographic response group/ # of submitted proposals with PIs from the same demographic response group

8.a.i.3. Race – PSD PIs

PSD PIs: Submitted Race - Plot



AIAN: American Indian and Alaska Native | NHOPI: Native Hawaiian and Other Pacific Islander | PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated.

Suppression categories: AIAN (All years), Black (ROSES 2021), NHOPI (All years).
See *Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics* for more information.

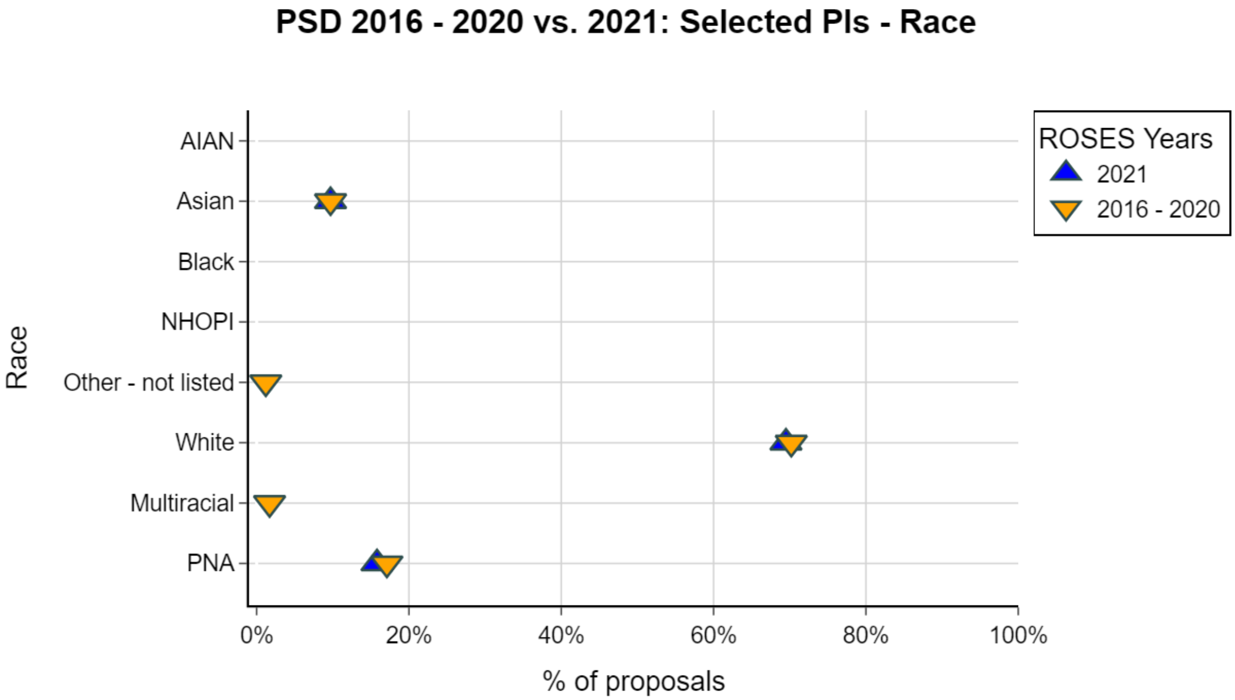
PSD PIs: Submitted Race - Data Table

PSD 2016 - 2020 vs. 2021: Submitted PIs - Race

Race	PSD 2016 - 2020	PSD 2021
AIAN	NR	NR
Asian	10%	12%
Black	< 1%	NR
NHOPI	NR	NR
Other - not listed	2%	2%
White	67%	67%
Multiracial	2%	3%
PNA	19%	15%

AIAN: American Indian and Alaska Native | NHOPI: Native Hawaiian and Other Pacific Islander | PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

PSD PIs: Selected Race - Plot



AIAN: American Indian and Alaska Native | NHOPI: Native Hawaiian and Other Pacific Islander | PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated.

Suppression categories: AIAN (All years), Black (All years), NHOPI (All years), Other – not listed (ROSES 2021), Multiracial (ROSES 2021).
See *Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics* for more information.

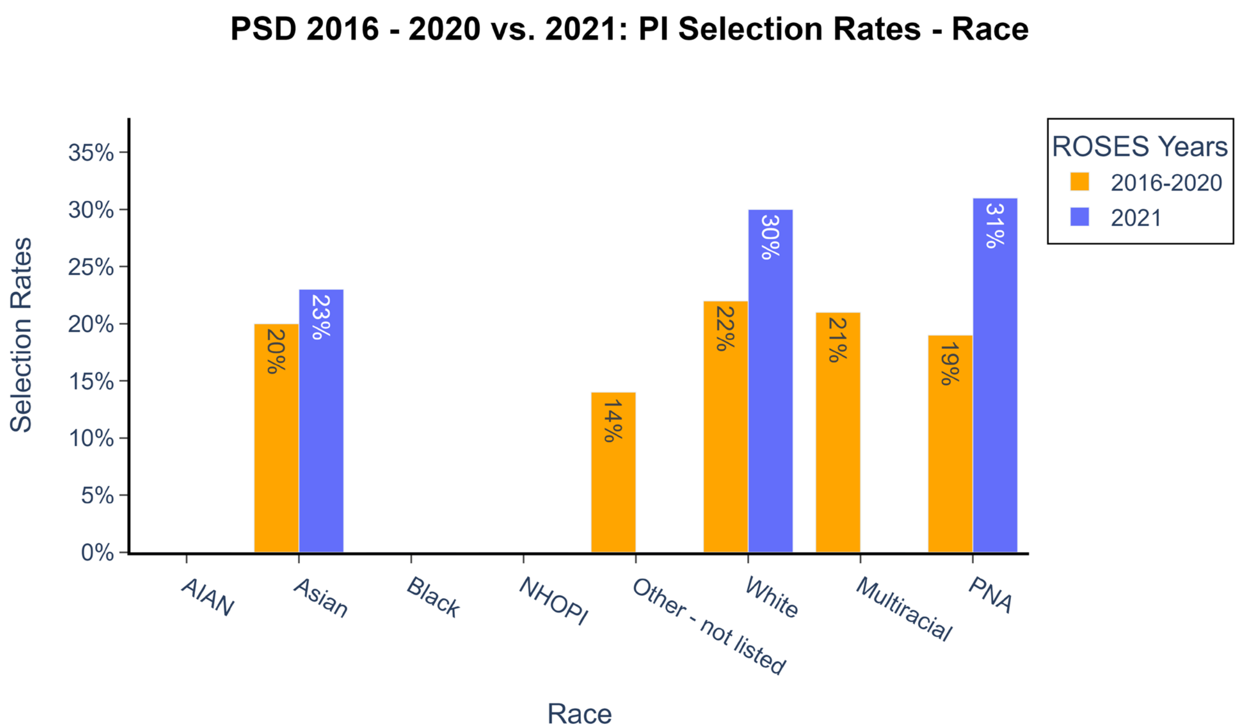
PSD PIs: Selected Race - Data Table

PSD 2016 - 2020 vs. 2021: Selected PIs - Race

Race	PSD 2016 - 2020	PSD 2021
AIAN	NR	NR
Asian	10%	10%
Black	NR	NR
NHOPI	NR	NR
Other - not listed	1%	NR
White	70%	70%
Multiracial	2%	NR
PNA	17%	16%

AIAN: American Indian and Alaska Native | NHOPI: Native Hawaiian and Other Pacific Islander | PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

PSD PIs: Race Selection Rate - Bar Plot



AIAN: American Indian and Alaska Native | NHOPI: Native Hawaiian and Other Pacific Islander | PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated. | Selection rate = # of selected proposals with PIs from a demographic response group/ # of submitted proposals with PIs from the same demographic response group

Suppression categories: AIAN (All years), Black (All years), NHOPI (All years), Other – not listed (ROSES 2021), Multiracial (ROSES 2021).
See *Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics* for more information.

PSD PIs: Race Selection Rate - Data Table

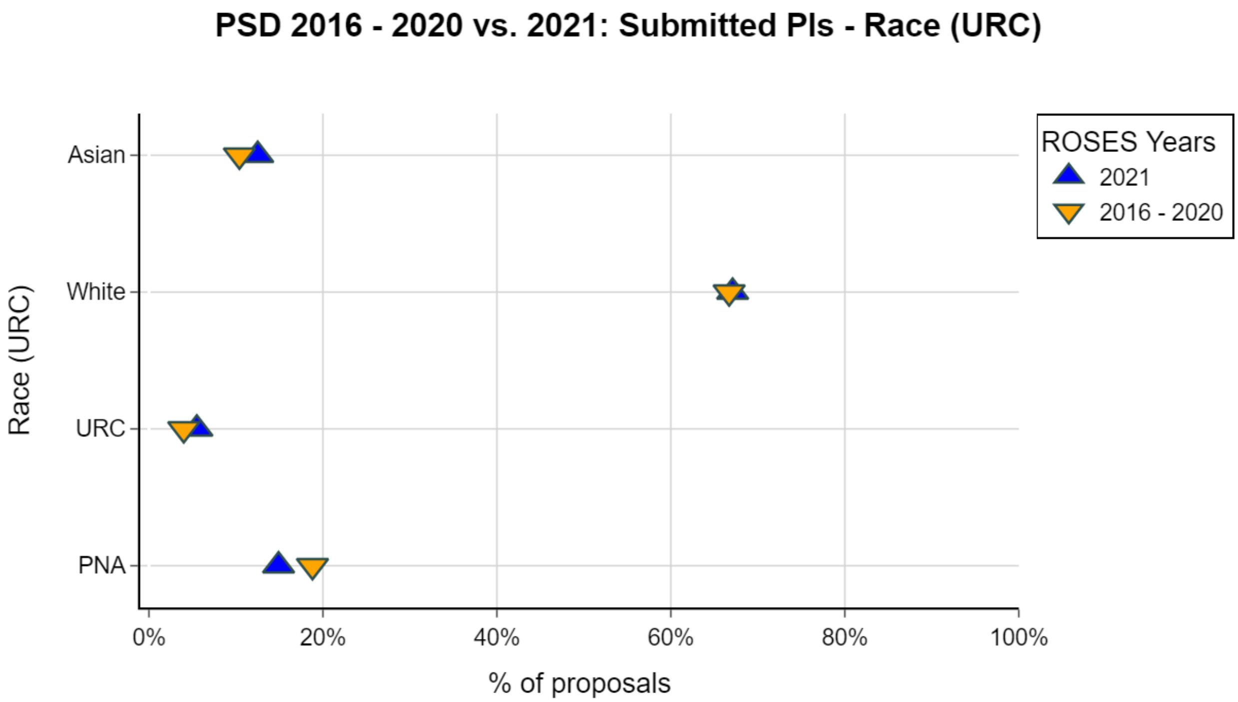
PSD 2016 - 2020 vs. 2021: PI Selection Rates - Race

Race	PSD 2016-2020	PSD 2016-2020 Response/All Races	PSD 2021	PSD 2021 Response/All Races
AIAN	NR	NR	NR	NR
Asian	20%	0.95	23%	0.79
Black	NR	NR	NR	NR
NHOPI	NR	NR	NR	NR
Other - not listed	14%	0.67	NR	NR
White	22%	1.05	30%	1.03
Multiracial	21%	1	NR	NR
PNA	19%	0.9	31%	1.07
All Races	21%	1	29%	1

AIAN: American Indian and Alaska Native | NHOPI: Native Hawaiian and Other Pacific Islander | PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated. | Selection rate = # of selected proposals with PIs from a demographic response group/ # of submitted proposals with PIs from the same demographic response group

8.a.i.4. Race using Under-Represented Community (URC) – PSD PIs

PSD PIs: Submitted Race (URC) - Plot



Under-Represented Community (URC) includes American Indian & Alaska Native, Black, Native Hawaiian & Other Pacific Islander, Multiracial, Other. | PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated.

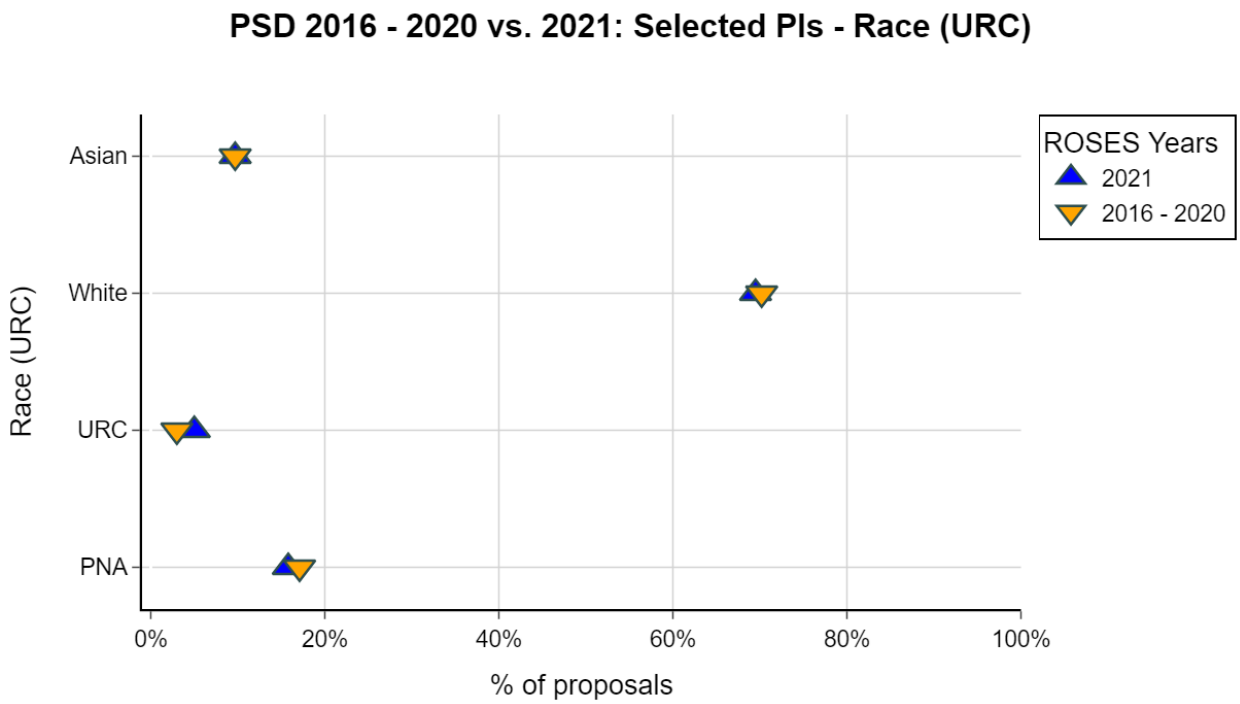
PSD PIs: Submitted Race (URC) - Data Table

PSD 2016 - 2020 vs. 2021: Submitted PIs - Race (URC)

Race (URC)	PSD 2016 - 2020	PSD 2021
Asian	10%	12%
White	67%	67%
URC	4%	6%
PNA	19%	15%

Under-Represented Community (URC) includes American Indian & Alaska Native, Black, Native Hawaiian & Other Pacific Islander, Multiracial, and Other. | PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

PSD PIs: Selected Race (URC) - Plot



Under-Represented Community (URC) includes American Indian & Alaska Native, Black, Native Hawaiian & Other Pacific Islander, Multiracial, and Other. | PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated.

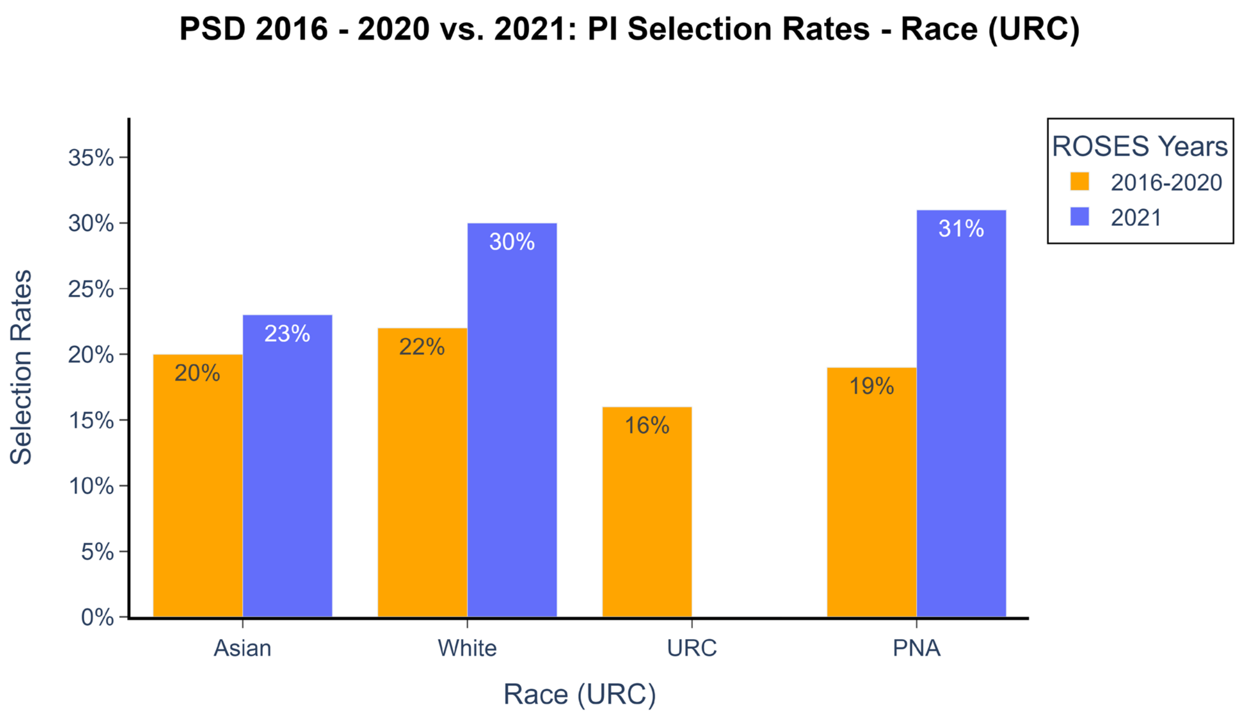
PSD PIs: Selected Race (URC) - Data Table

PSD 2016 - 2020 vs. 2021: Selected PIs - Race (URC)

Race (URC)	PSD 2016 - 2020	PSD 2021
Asian	10%	10%
White	70%	70%
URC	3%	5%
PNA	17%	16%

Under-Represented Community (URC) includes American Indian & Alaska Native, Black, Native Hawaiian & Other Pacific Islander, Multiracial, and Other. | PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

PSD PIs: Race (URC) Selection Rate - Bar Plot



Under-Represented Community (URC) includes American Indian & Alaska Native, Black, Native Hawaiian & Other Pacific Islander, Multiracial, and Other. | PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated. | Selection rate = # of selected proposals with PIs from a demographic response group/ # of submitted proposals with PIs from the same demographic response group

Suppression categories: URC (ROSES 2021).
See *Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics* for more information.

PSD PIs: Race (URC) Selection Rate - Data Table

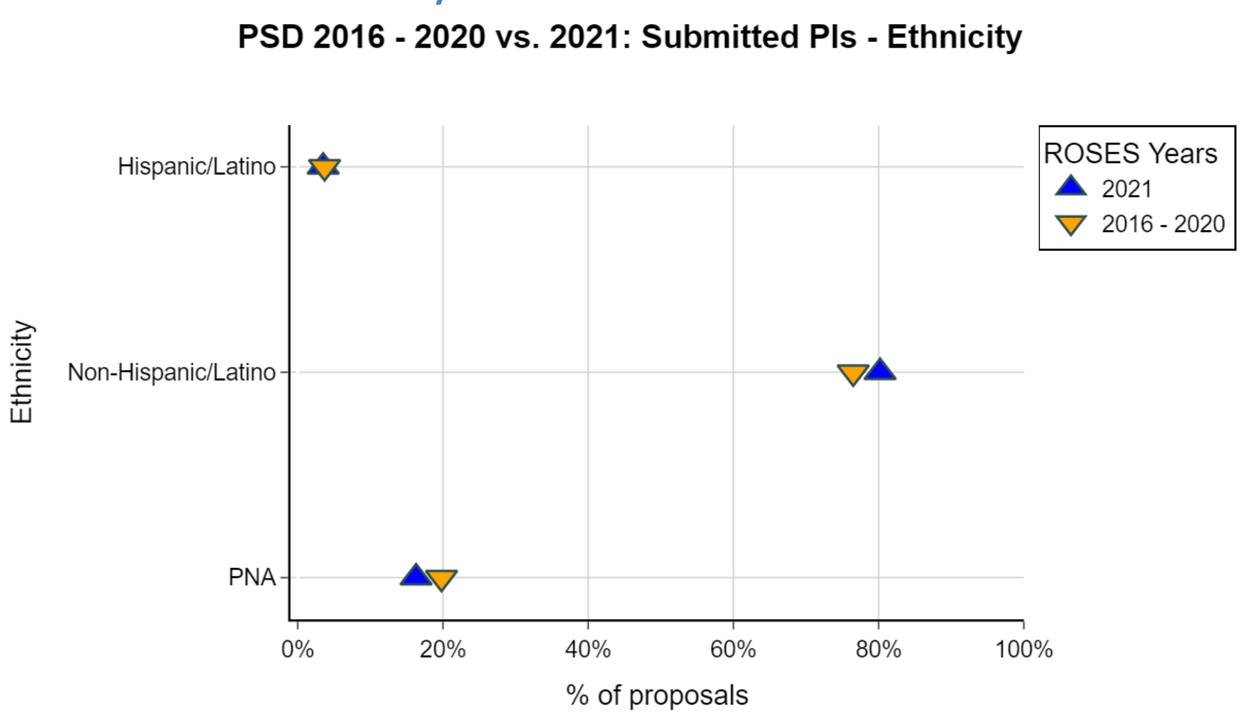
PSD 2016 - 2020 vs. 2021: PI Selection Rates - Race (URC)

Race (URC)	PSD 2016-2020	PSD 2016-2020 Response/All Races (URC)	PSD 2021	PSD 2021 Response/All Races (URC)
Asian	20%	0.95	23%	0.79
White	22%	1.05	30%	1.03
URC	16%	0.76	NR	NR
PNA	19%	0.9	31%	1.07
All Races (URC)	21%	1	29%	1

Under-Represented Community (URC) includes American Indian & Alaska Native, Black, Native Hawaiian & Other Pacific Islander, Multiracial, and Other. | PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated. | Selection rate = # of selected proposals with PIs from a demographic response group/ # of submitted proposals with PIs from the same demographic response group

8.a.i.5. Ethnicity – PSD PIs

PSD PIs: Submitted Ethnicity - Plot



PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated.

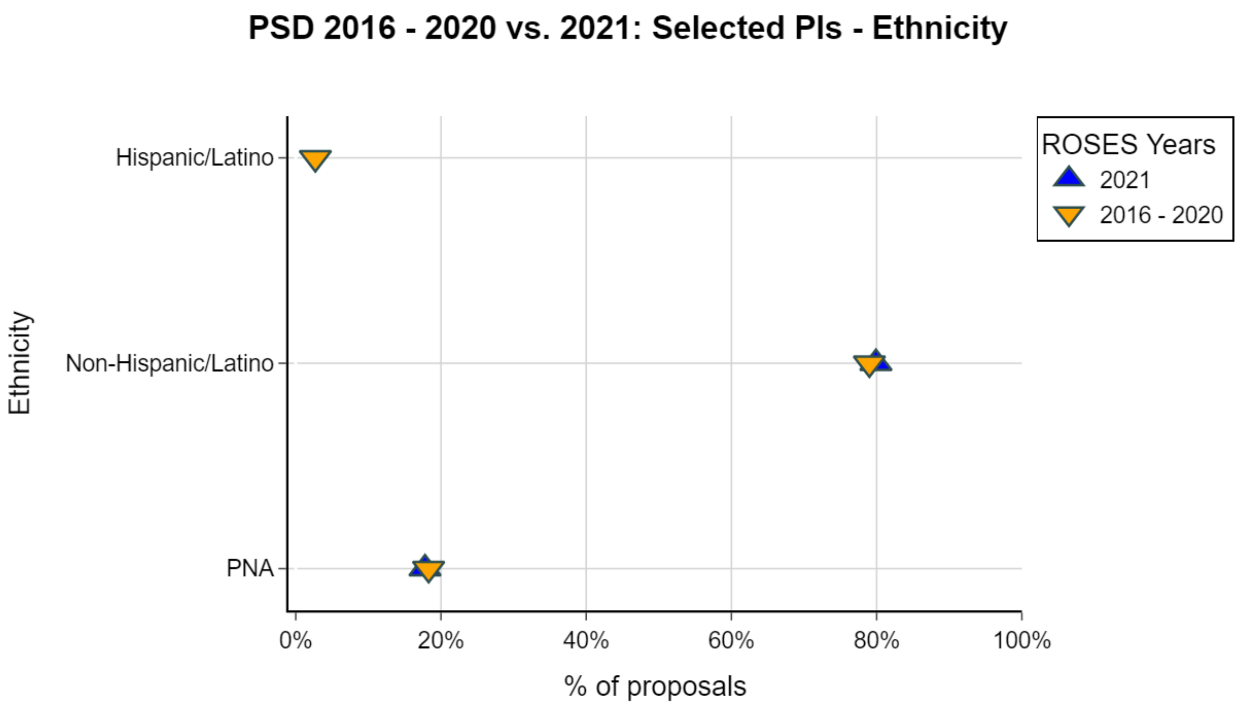
PSD PIs: Submitted Ethnicity - Data Table

PSD 2016 - 2020 vs. 2021: Submitted PIs - Ethnicity

Ethnicity	PSD 2016 - 2020	PSD 2021
Hispanic/Latino	4%	4%
Non-Hispanic/Latino	76%	80%
PNA	20%	16%

PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

PSD PIs: Selected Ethnicity - Plot



PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated.

Suppression categories: Hispanic/Latino (ROSES 2021).
See *Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics* for more information.

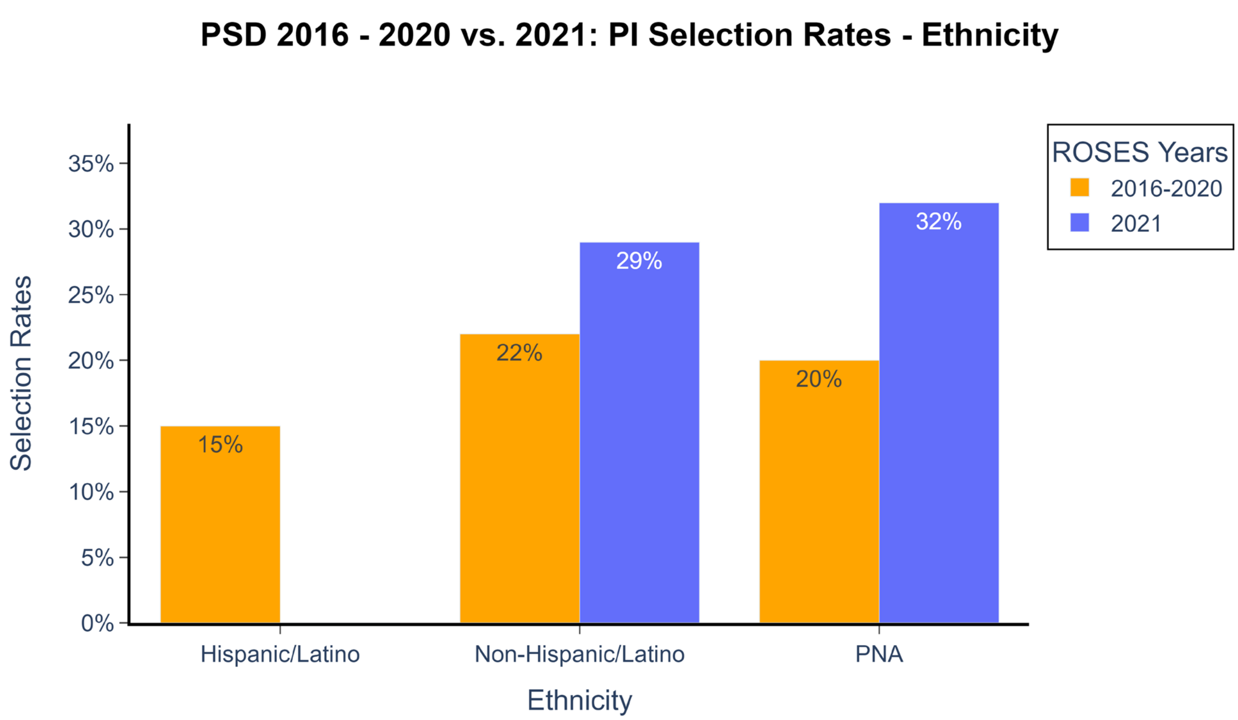
PSD PIs: Selected Ethnicity - Data Table

PSD 2016 - 2020 vs. 2021: Selected PIs - Ethnicity

Ethnicity	PSD 2016 - 2020	PSD 2021
Hispanic/Latino	3%	NR
Non-Hispanic/Latino	79%	80%
PNA	18%	18%

PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

PSD PIs: Ethnicity Selection Rate - Bar Plot



PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated. | Selection rate = # of selected proposals with PIs from a demographic response group/ # of submitted proposals with PIs from the same demographic response group

Suppression categories: Hispanic/Latino (ROSES 2021).
See *Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics* for more information.

PSD PIs: Ethnicity Selection Rate - Data Table

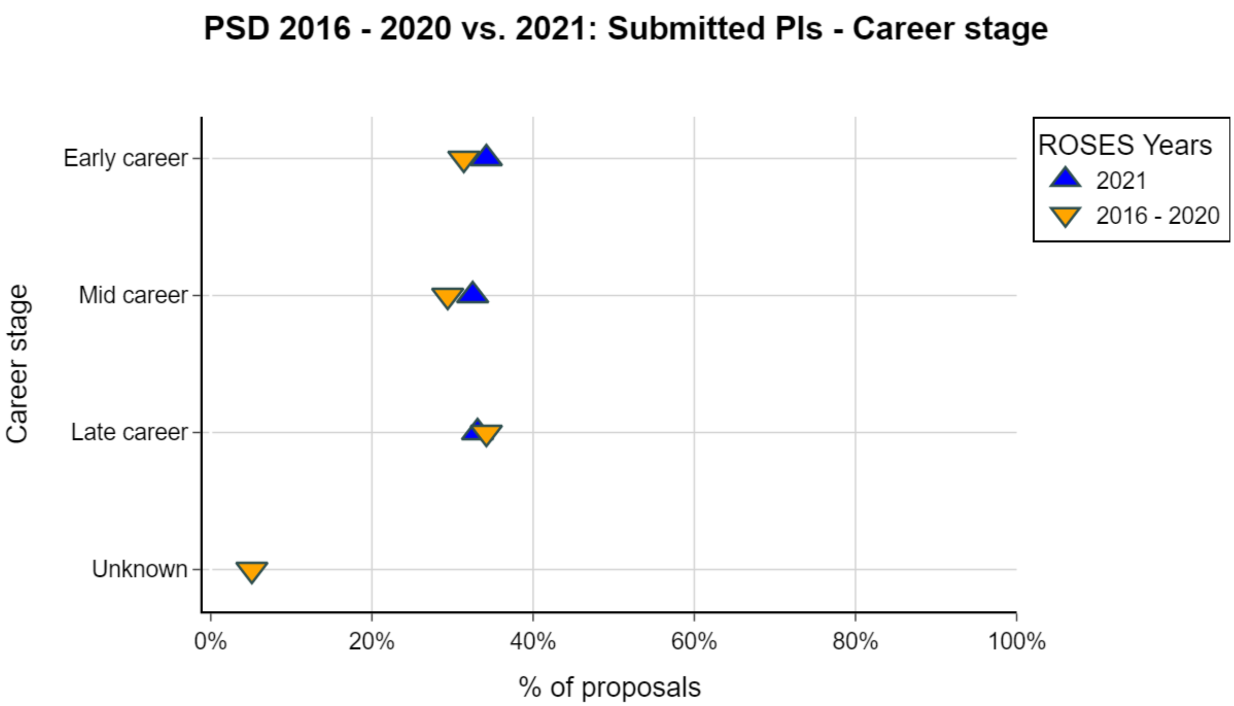
PSD 2016 - 2020 vs. 2021: PI Selection Rates - Ethnicity

Ethnicity	PSD 2016-2020	PSD 2016-2020 Response/All Ethnicities	PSD 2021	PSD 2021 Response/All Ethnicities
Hispanic/Latino	15%	0.71	NR	NR
Non-Hispanic/Latino	22%	1.05	29%	1
PNA	20%	0.95	32%	1.1
All Ethnicities	21%	1	29%	1

PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated. | Selection rate = # of selected proposals with PIs from a demographic response group/ # of submitted proposals with PIs from the same demographic response group

8.a.i.6. Career Stage – PSD PIs

PSD PIs: Submitted Career Stage - Plot



Early career: < 10 years since earning final degree | Mid career: 10 - 19 years since earning final degree | Late career: 20+ years since earning final degree | ROSES 2016-2020 proposal data are aggregated.

Suppression categories: Unknown (ROSES 2021).
See *Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics* for more information.

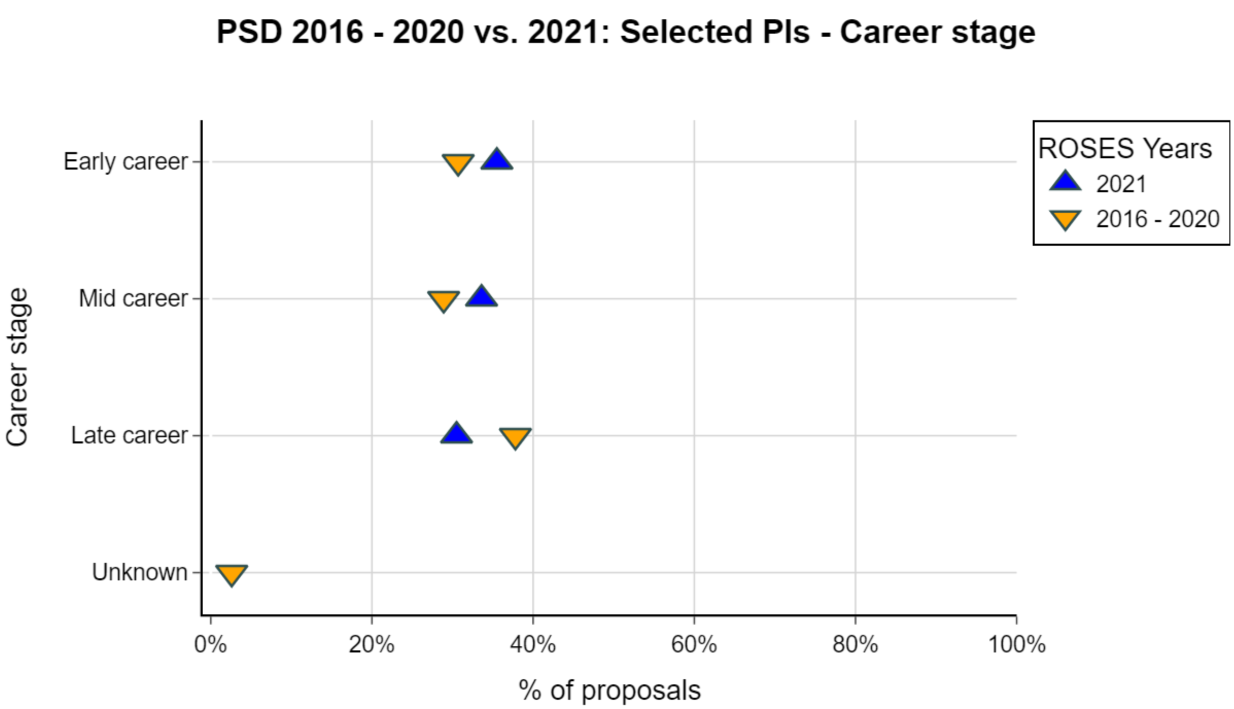
PSD PIs: Submitted Career Stage - Data Table

PSD 2016 - 2020 vs. 2021: Submitted PIs - Career stage

Career stage	PSD 2016 - 2020	PSD 2021
Early career	31%	34%
Mid career	29%	32%
Late career	34%	33%
Unknown	5%	NR

Early career: < 10 years since earning final degree | Mid career: 10 - 19 years since earning final degree | Late career: 20+ years since earning final degree | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

PSD PIs: Selected Career Stage - Plot



Early career: < 10 years since earning final degree | Mid career: 10 - 19 years since earning final degree | Late career: 20+ years since earning final degree | ROSES 2016-2020 proposal data are aggregated.

Suppression categories: Unknown (ROSES 2021).
See *Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics* for more information.

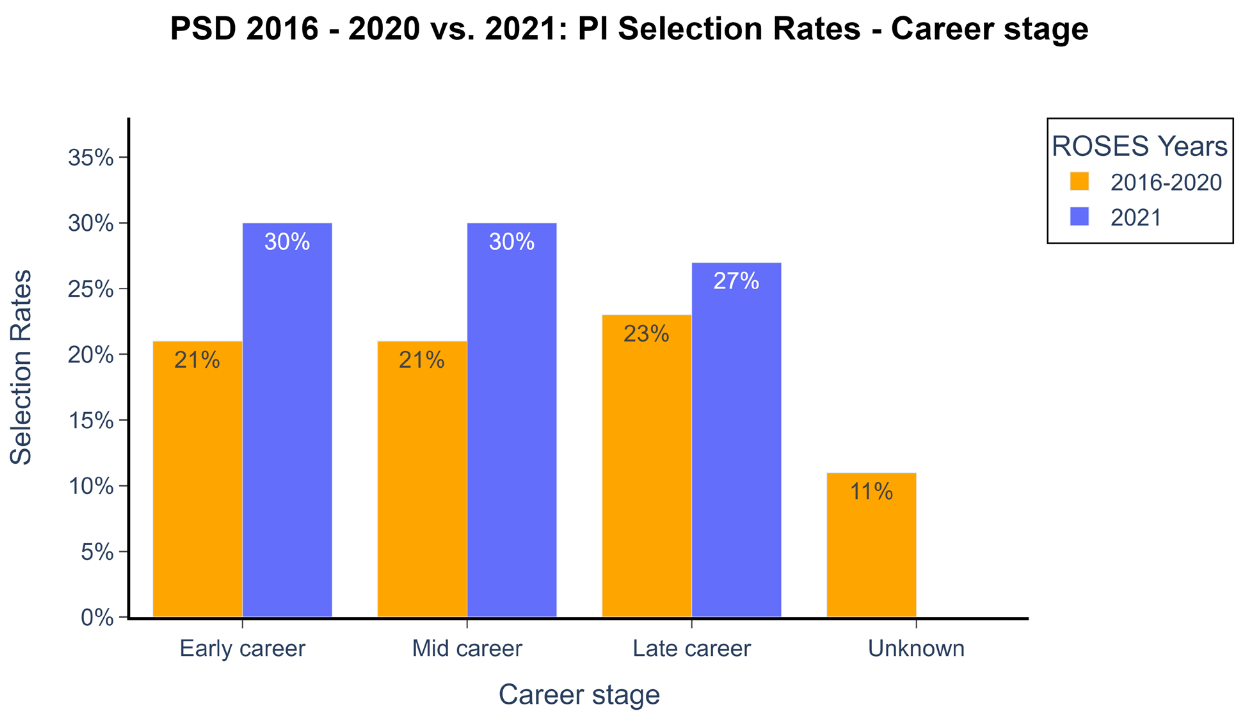
PSD PIs: Selected Career Stage - Data Table

PSD 2016 - 2020 vs. 2021: Selected PIs - Career stage

Career stage	PSD 2016 - 2020	PSD 2021
Early career	31%	36%
Mid career	29%	34%
Late career	38%	30%
Unknown	3%	NR

Early career: < 10 years since earning final degree | Mid career: 10 - 19 years since earning final degree | Late career: 20+ years since earning final degree | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

PSD PIs: Career Stage Selection Rate - Bar Plot



Early career: < 10 years since earning final degree | Mid career: 10 - 19 years since earning final degree | Late career: 20+ years since earning final degree | ROSES 2016-2020 proposal data are aggregated. | Selection rate = # of selected proposals with PIs from a demographic response group/ # of submitted proposals with PIs from the same demographic response group

Suppression categories: Unknown (ROSES 2021).
See *Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics* for more information.

PSD PIs: Career Stage Selection Rate - Data Table

PSD 2016 - 2020 vs. 2021: PI Selection Rates - Career stage

Career stage	PSD 2016-2020	PSD 2016-2020 Response/All Career stages	PSD 2021	PSD 2021 Response/All Career stages
Early career	21%	1	30%	1.03
Mid career	21%	1	30%	1.03
Late career	23%	1.1	27%	0.93
Unknown	11%	0.52	NR	NR
All Career stages	21%	1	29%	1

Early career: < 10 years since earning final degree | Mid career: 10 - 19 years since earning final degree | Late career: 20+ years since earning final degree | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated. | Selection rate = # of selected proposals with PIs from a demographic response group/ # of submitted proposals with PIs from the same demographic response group

8.a.i.7. Disability Status – PSD PIs

PSD PIs: Submitted Ability - Plot

Disabled includes hearing, visual, mobility/orthopedic, and other impairment. | PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated.

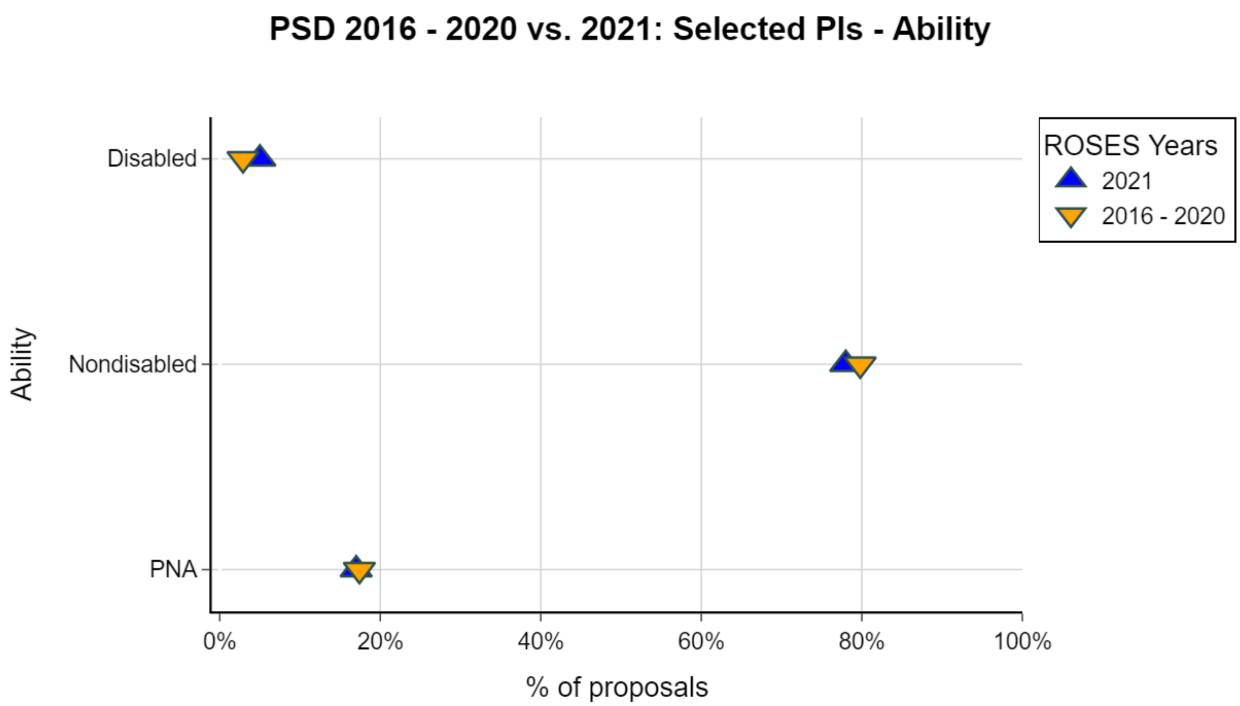
PSD PIs: Submitted Ability - Data Table

PSD 2016 - 2020 vs. 2021: Submitted PIs - Ability

Ability	PSD 2016 - 2020	PSD 2021
Disabled	4%	4%
Nondisabled	78%	81%
PNA	18%	16%

Disabled includes hearing, visual, mobility/orthopedic, and other impairment. | PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

PSD PIs: Selected Ability - Plot



Disabled includes hearing, visual, mobility/orthopedic, and other impairment. | PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated.

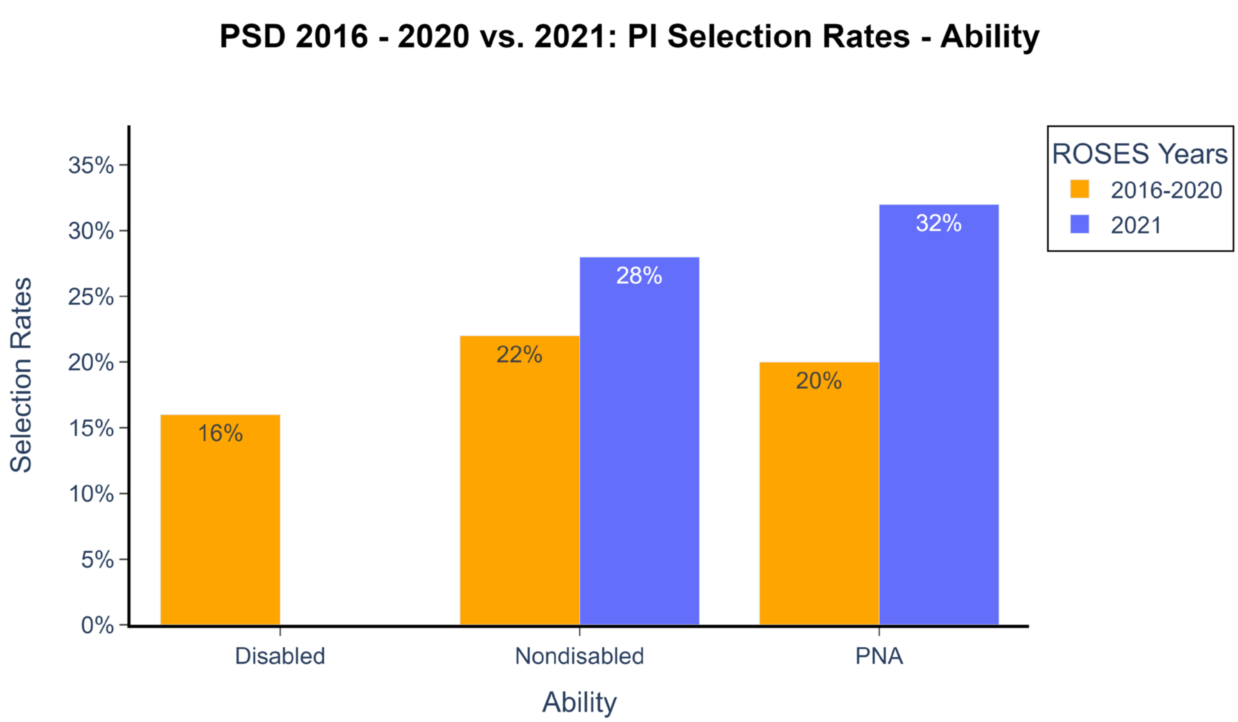
PSD PIs: Selected Ability - Data Table

PSD 2016 - 2020 vs. 2021: Selected PIs - Ability

Ability	PSD 2016 - 2020	PSD 2021
Disabled	3%	5%
Nondisabled	80%	78%
PNA	17%	17%

Disabled includes hearing, visual, mobility/orthopedic, and other impairment. | PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

PSD PIs: Ability Selection Rate - Bar Plot



Disabled includes hearing, visual, mobility/orthopedic, and other impairment. | PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated. | Selection rate = # of selected proposals with PIs from a demographic response group/ # of submitted proposals with PIs from the same demographic response group

Suppression categories: Disabled (ROSES 2021).
See *Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics* for more information.

PSD PIs: Ability Selection Rate - Data Table

PSD 2016 - 2020 vs. 2021: PI Selection Rates - Ability

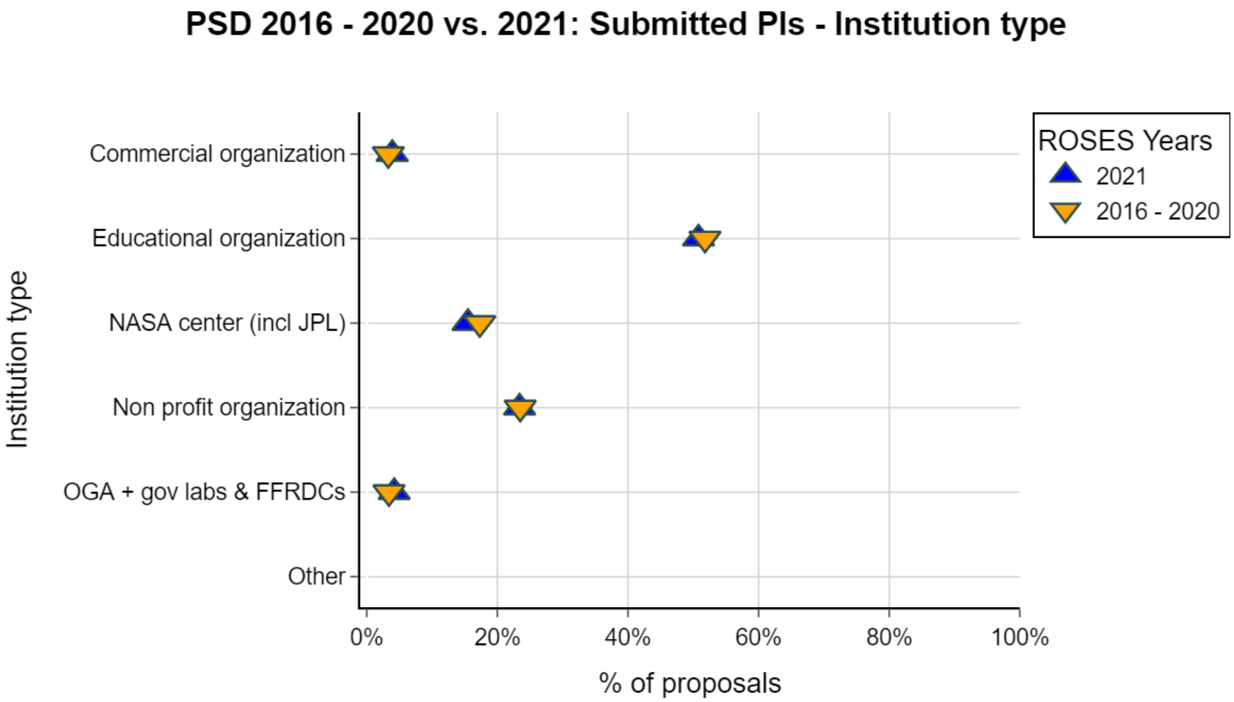
Ability	PSD 2016-2020	PSD 2016-2020 Response/All Abilities	PSD 2021	PSD 2021 Response/All Abilities
Disabled	16%	0.76	NR	NR
Nondisabled	22%	1.05	28%	0.97
PNA	20%	0.95	32%	1.1
All Abilities	21%	1	29%	1

Disabled includes hearing, visual, mobility/orthopedic, and other impairment. | PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated. | Selection rate = # of selected proposals with PIs from a demographic response group/ # of submitted proposals with PIs from the same demographic response group

8.a.i.8. Institutional Analysis

8.a.i.8.a. Institution Type

PSD PIs: Submitted Institution Type - Plot



OGA: Other Government Agency | FFRDCs: Federally Funded Research and Development Centers | Other: State, Local or Federally Recognized Tribal Government Agency & Unaffiliated Individuals | ROSES 2016-2020 proposal data are aggregated.

Suppression categories: Other (All years).
See *Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics* for more information.

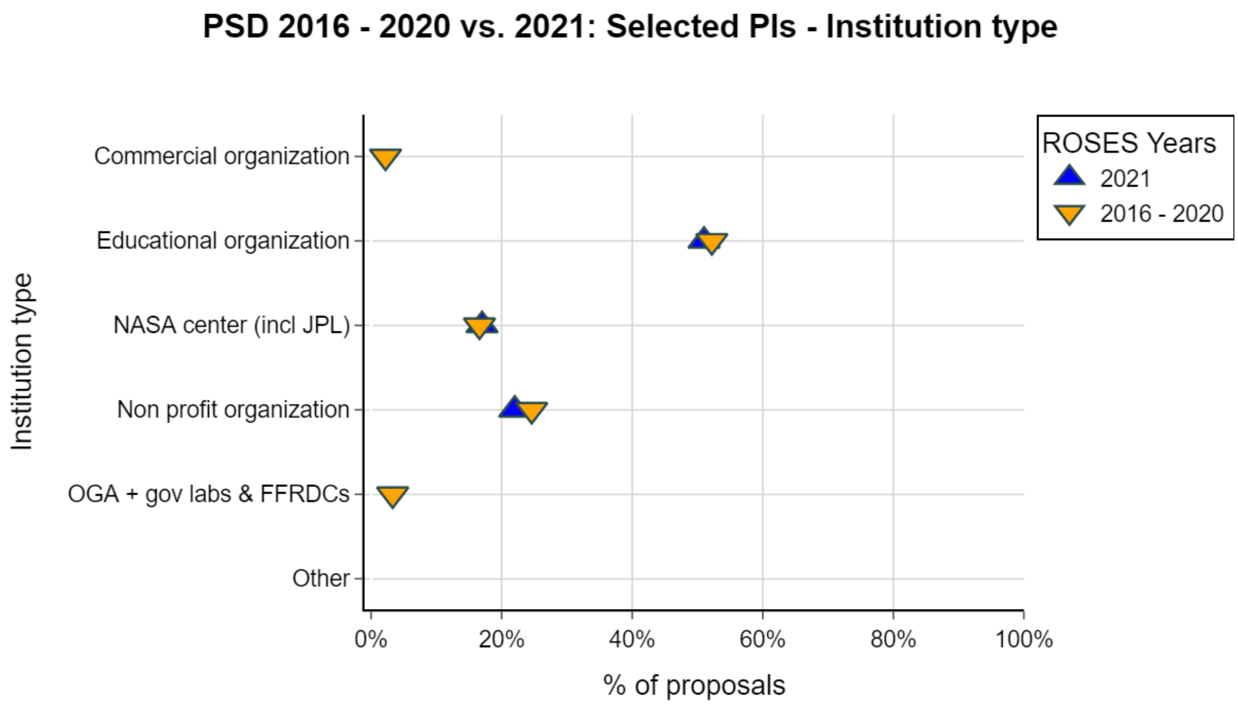
PSD PIs: Submitted Institution Type - Data Table

PSD 2016 - 2020 vs. 2021: Submitted PIs - Institution type

Institution type	PSD 2016 - 2020	PSD 2021
Commercial organization	3%	4%
Educational organization	52%	51%
NASA center (incl JPL)	17%	16%
Non profit organization	24%	23%
OGA + gov labs & FFRDCs	3%	4%
Other	NR	NR

OGA: Other Government Agency | FFRDCs: Federally Funded Research and Development Centers | Other: State, Local or Federally Recognized Tribal Government Agency & Unaffiliated Individuals | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

PSD PIs: Selected Institution Type - Plot



OGA: Other Government Agency | FFRDCs: Federally Funded Research and Development Centers | Other: State, Local or Federally Recognized Tribal Government Agency & Unaffiliated Individuals | ROSES 2016-2020 proposal data are aggregated.

Suppression categories: Commercial organization (ROSES 2021), OGA + gov labs & FFRDCs (ROSES 2021), Other (All years).
See *Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics* for more information.

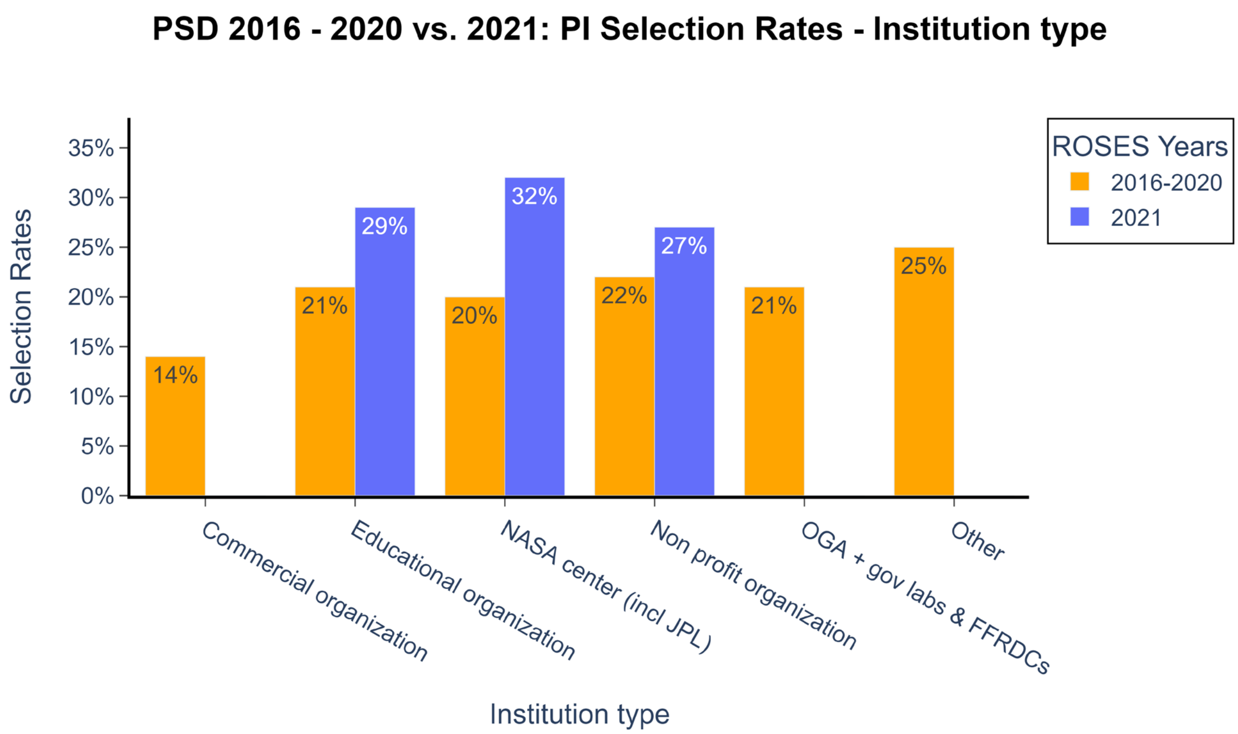
PSD PIs: Selected Institution Type - Data Table

PSD 2016 - 2020 vs. 2021: Selected PIs - Institution type

Institution type	PSD 2016 - 2020	PSD 2021
Commercial organization	2%	NR
Educational organization	52%	51%
NASA center (incl JPL)	17%	17%
Non profit organization	25%	22%
OGA + gov labs & FFRDCs	3%	NR
Other	NR	NR

OGA: Other Government Agency | FFRDCs: Federally Funded Research and Development Centers | Other: State, Local or Federally Recognized Tribal Government Agency & Unaffiliated Individuals | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

PSD PIs: Institution Type Selection Rate - Bar Plot



OGA: Other Government Agency | FFRDCs: Federally Funded Research and Development Centers | Other: State, Local or Federally Recognized Tribal Government Agency & Unaffiliated Individuals | ROSES 2016-2020 proposal data are aggregated. | Selection rate = # of selected proposals with PIs from a demographic response group/ # of submitted proposals with PIs from the same demographic response group

Suppression categories: Commercial organization (ROSES 2021), OGA + gov labs & FFRDCs (ROSES 2021), Other (ROSES 2021).
See *Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics* for more information.

PSD PIs: Institution Type Selection Rate - Data Table

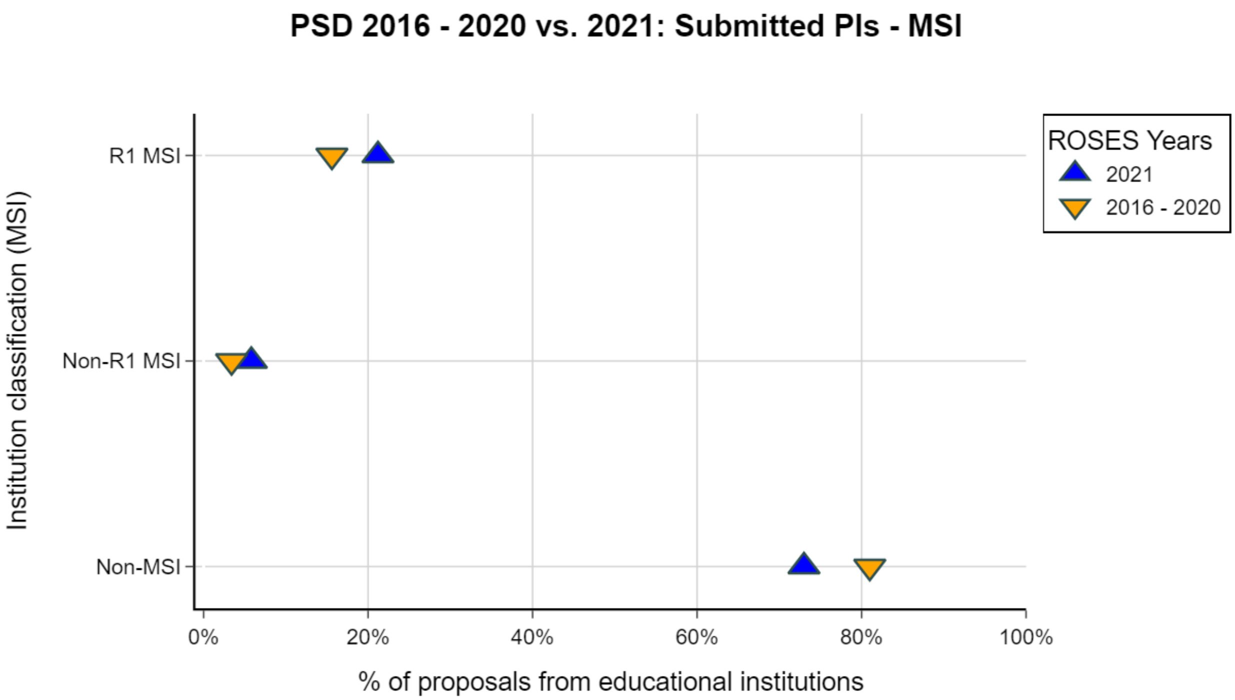
PSD 2016 - 2020 vs. 2021: PI Selection Rates - Institution type

Institution type	PSD 2016-2020	PSD 2016-2020 Response/All Institution types	PSD 2021	PSD 2021 Response/All Institution types
Commercial organization	14%	0.67	NR	NR
Educational organization	21%	1	29%	1
NASA center (incl JPL)	20%	0.95	32%	1.1
Non profit organization	22%	1.05	27%	0.93
OGA + gov labs & FFRDCs	21%	1	NR	NR
Other	25%	1.19	NR	NR
All Institution types	21%	1	29%	1

OGA: Other Government Agency | FFRDCs: Federally Funded Research and Development Centers | Other: State, Local or Federally Recognized Tribal Government Agency & Unaffiliated Individuals | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated. | Selection rate = # of selected proposals with PIs from a demographic response group/ # of submitted proposals with PIs from the same demographic response group

8.a.i.8.b. Minority Serving Institutions (MSIs)

PSD PIs: Submitted MSI - Plot



MSI: Minority Serving Institution | R1: Doctoral university - Very high research activity | ROSES 2016-2020 proposal data are aggregated.

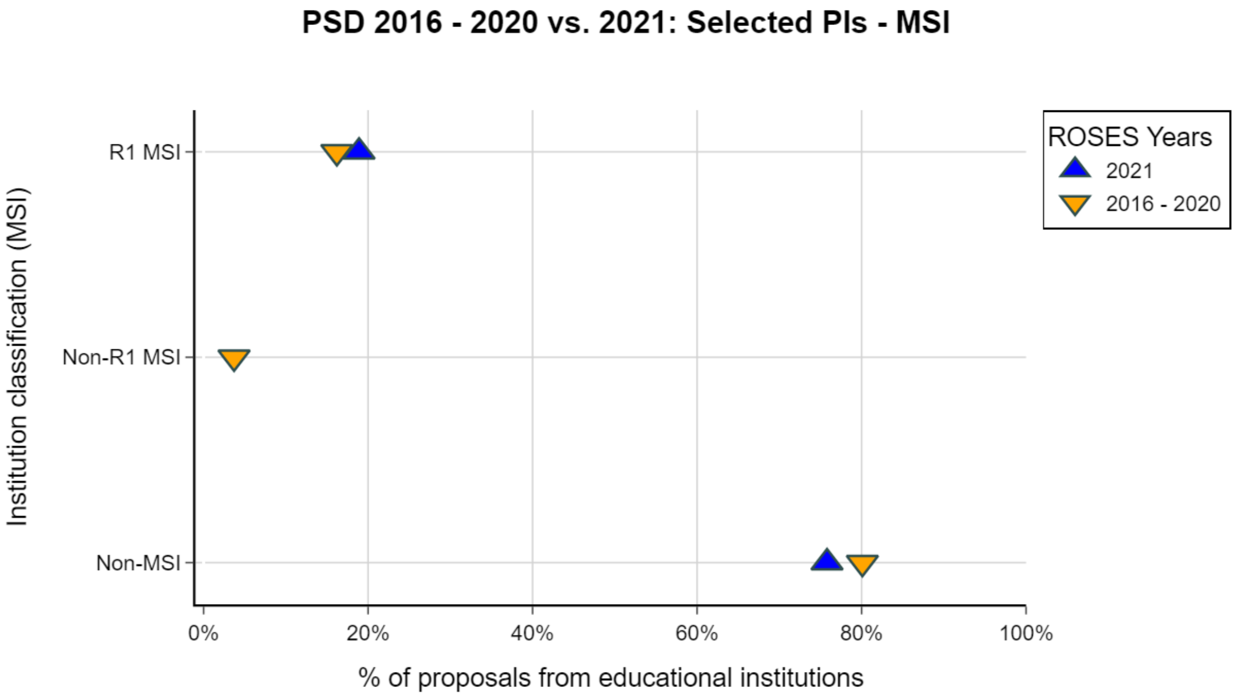
PSD PIs: Submitted MSI - Data Table

PSD 2016 - 2020 vs. 2021: Submitted PIs - MSI

MSI	PSD 2016 - 2020	PSD 2021
R1 MSI	16%	21%
Non-R1 MSI	3%	6%
Non-MSI	81%	73%

MSI: Minority Serving Institution | R1: Doctoral university - Very high research activity | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

PSD PIs: Selected MSI - Plot



MSI: Minority Serving Institution | R1: Doctoral university - Very high research activity | ROSES 2016-2020 proposal data are aggregated.

Suppression categories: Non-R1 MSI (ROSES 2021).
See *Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics* for more information.

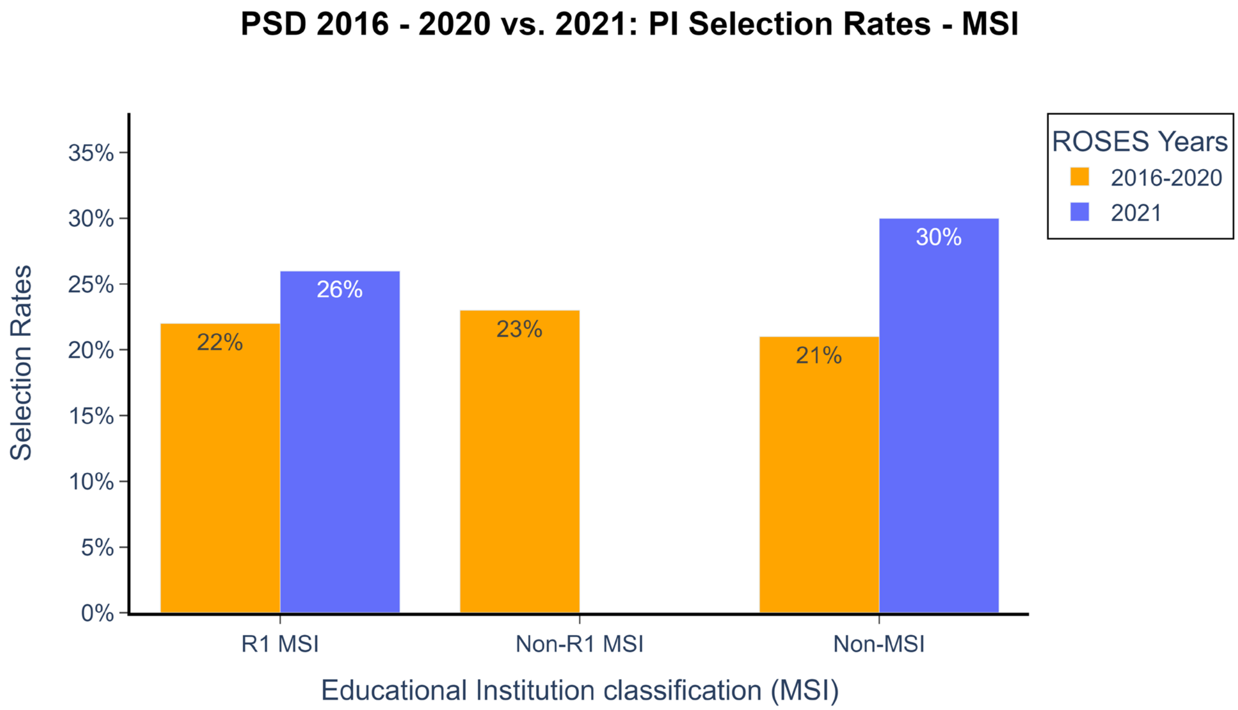
PSD PIs: Selected MSI - Data Table

PSD 2016 - 2020 vs. 2021: Selected PIs - MSI

MSI	PSD 2016 - 2020	PSD 2021
R1 MSI	16%	19%
Non-R1 MSI	4%	NR
Non-MSI	80%	76%

MSI: Minority Serving Institution | R1: Doctoral university - Very high research activity | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

PSD PIs: MSI Selection Rate - Bar Plot



MSI: Minority Serving Institution | R1: Doctoral university - Very high research activity | ROSES 2016-2020 proposal data are aggregated. | Selection rate = # of selected proposals with PIs from a demographic response group/ # of submitted proposals with PIs from the same demographic response group

Suppression categories: Non-R1 MSI (ROSES 2021).
See *Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics* for more information.

PSD PIs: MSI Selection Rate - Data Table

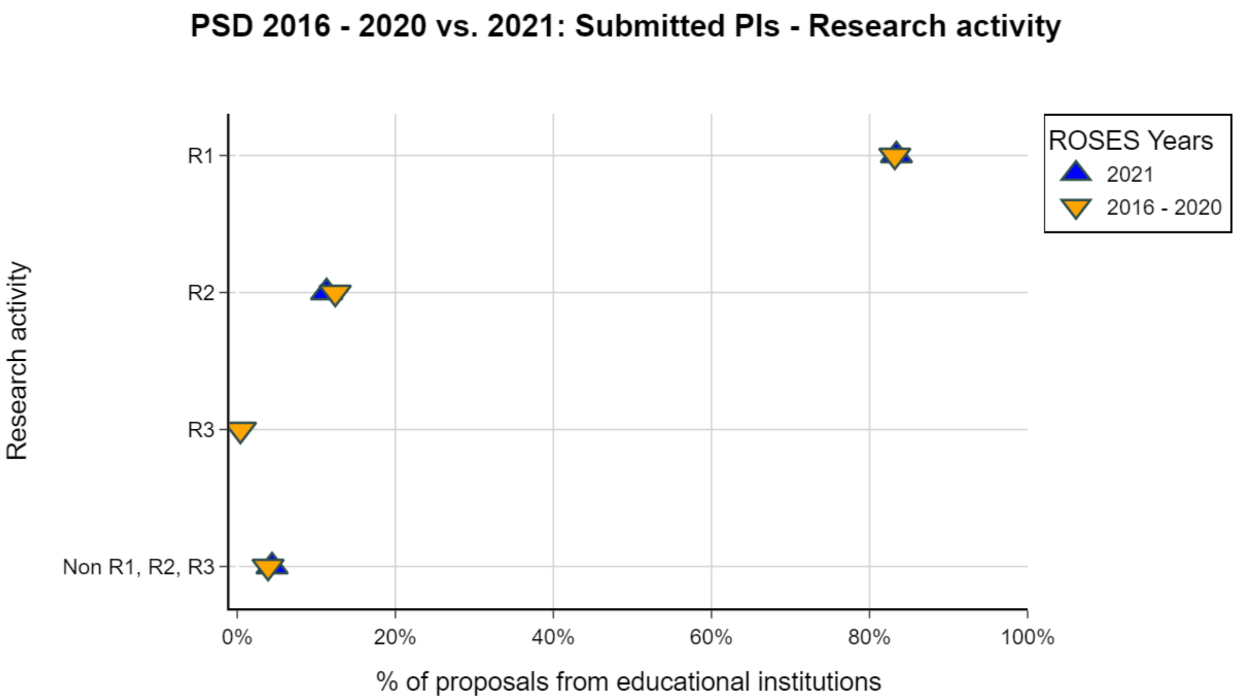
PSD 2016 - 2020 vs. 2021: PI Selection Rates - MSI

MSI	PSD 2016-2020	PSD 2016-2020 Response/All Educational Institutions	PSD 2021	PSD 2021 Response/All Educational Institutions
R1 MSI	22%	1.05	26%	0.9
Non-R1 MSI	23%	1.1	NR	NR
Non-MSI	21%	1	30%	1.03
All Educational Institutions	21%	1	29%	1

MSI: Minority Serving Institution | R1: Doctoral university - Very high research activity | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated. | Selection rate = # of selected proposals with PIs from a demographic response group/ # of submitted proposals with PIs from the same demographic response group

8.a.i.8.c. Carnegie Classification of Research Activity

PSD PIs: Submitted Research Activity - Plot



R1: Doctoral university - Very high research activity | R2: Doctoral university - High research activity | R3: Doctoral/professional university | ROSES 2016-2020 proposal data are aggregated.

Suppression categories: R3 (ROSES 2021).
See *Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics* for more information.

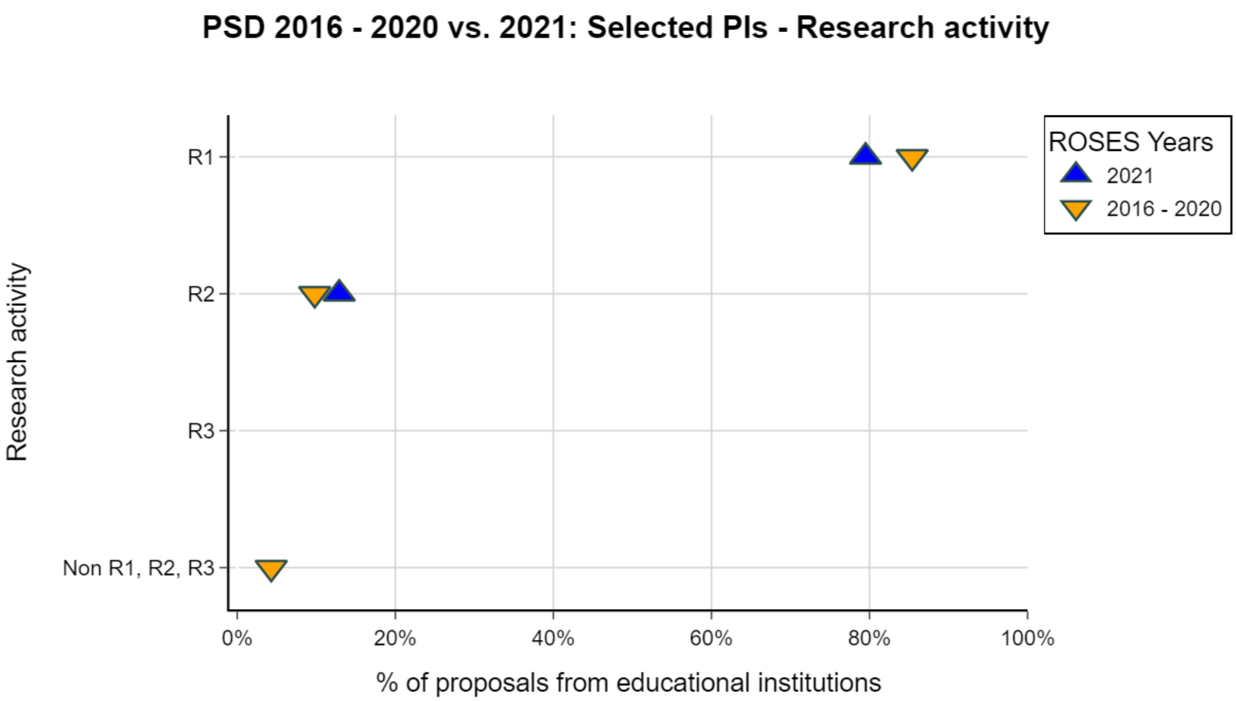
PSD PIs: Submitted Research Activity - Data Table

PSD 2016 - 2020 vs. 2021: Submitted PIs - Research activity

Research activity	PSD 2016 - 2020	PSD 2021
R1	83%	83%
R2	12%	11%
R3	< 1%	NR
Non R1, R2, R3	4%	4%

R1: Doctoral university - Very high research activity | R2: Doctoral university - High research activity | R3: Doctoral/professional university | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

PSD PIs: Selected Research Activity - Plot



R1: Doctoral university - Very high research activity | R2: Doctoral university - High research activity | R3: Doctoral/professional university | ROSES 2016-2020 proposal data are aggregated.

Suppression categories: R3 (All years), Non R1, R2, R3 (ROSES 2021).
See *Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics* for more information.

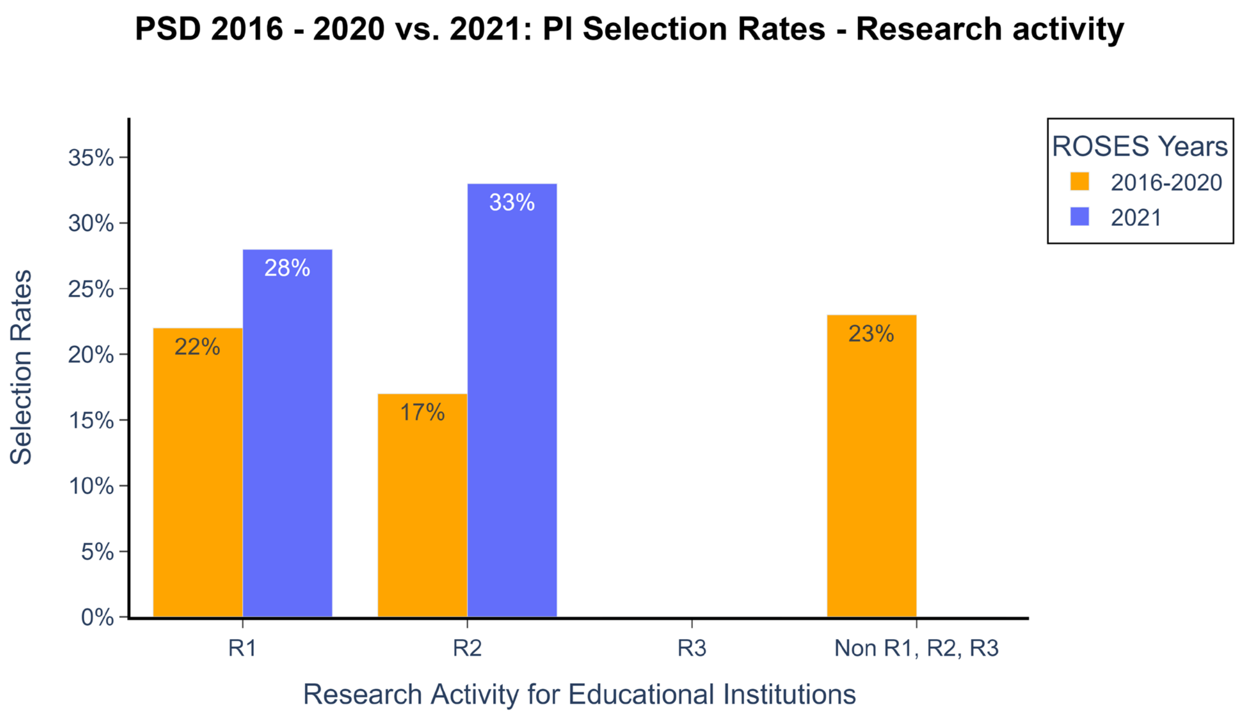
PSD PIs: Selected Research Activity - Data Table

PSD 2016 - 2020 vs. 2021: Selected PIs - Research activity

Research activity	PSD 2016 - 2020	PSD 2021
R1	85%	80%
R2	10%	13%
R3	NR	NR
Non R1, R2, R3	4%	NR

R1: Doctoral university - Very high research activity | R2: Doctoral university - High research activity | R3: Doctoral/professional university | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

PSD PIs: Research Activity Selection Rate - Bar Plot



R1: Doctoral university - Very high research activity | R2: Doctoral university - High research activity | R3: Doctoral/professional university | ROSES 2016-2020 proposal data are aggregated. | Selection rate = # of selected proposals with PIs from a demographic response group/ # of submitted proposals with PIs from the same demographic response group

Suppression categories: R3 (All years), Non R1, R2, R3 (ROSES 2021).
See *Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics* for more information.

PSD PIs: Research Activity Selection Rate - Data Table

PSD 2016 - 2020 vs. 2021: PI Selection Rates - Research activity

Research activity	PSD 2016-2020	PSD 2016-2020 Response/All Educational Institutions	PSD 2021	PSD 2021 Response/All Educational Institutions
R1	22%	1.05	28%	0.97
R2	17%	0.81	33%	1.14
R3	NR	NR	NR	NR
Non R1, R2, R3	23%	1.1	NR	NR
All Educational Institutions	21%	1	29%	1

R1: Doctoral university - Very high research activity | R2: Doctoral university - High research activity | R3: Doctoral/professional university | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated. | Selection rate = # of selected proposals with PIs from a demographic response group/ # of submitted proposals with PIs from the same demographic response group

8.a.ii. Science Team

8.a.ii.1. Limitations of the data – PSD Science team

26,043 submitted proposals are included in the ROSES 2016-2021 database. Please see Appendix Table 1 to see which programs are included. The total number of proposals submitted and selected for each ROSES year and the total number of proposals submitted to each SMD Division cannot be reported due to the Office of the Chief Scientist's suppression guidelines. See *Yearbook Introduction Section 1.a.ii.1* *Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics* for more information. The number of proposals rounded to the nearest hundred are included for these two circumstances to provide context. For the Planetary Science Division, there are ~8,200 submitted proposals over all ROSES years: ~7,300 for ROSES 2016-2020 and ~900 for ROSES 2021.

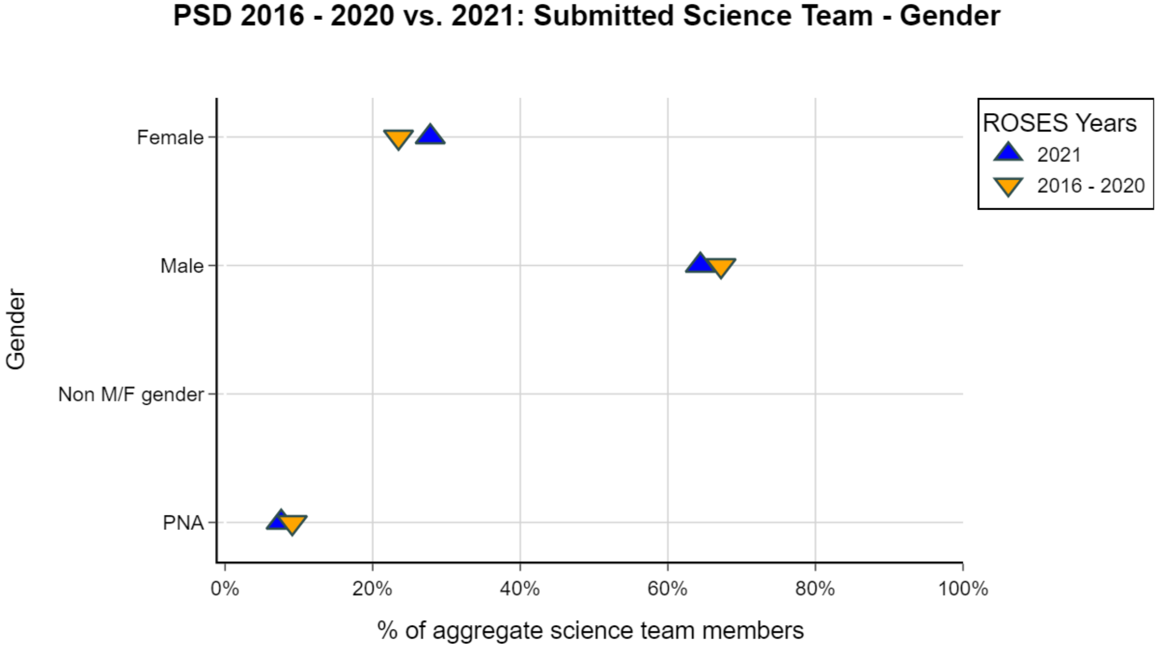
Instances in the science team member dataset where a science team member took the survey but selected "prefer not to answer" for all demographic survey questions:

- Submitted: PSD 2016 - 2020: 8% | PSD 2021: 7%
- Selected: PSD 2016 - 2020: 8% | PSD 2021: 6%

Demographic data responses for two Co-Is participating in PSD proposals in ROSES 2016 and 2017 are missing and have been removed from the dataset.

8.a.ii.2. Gender – PSD Science team

PSD Science Team: Submitted Gender - Plot



PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated.

Suppressed categories: Non M/F gender (All years).
See *Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics* for more information.

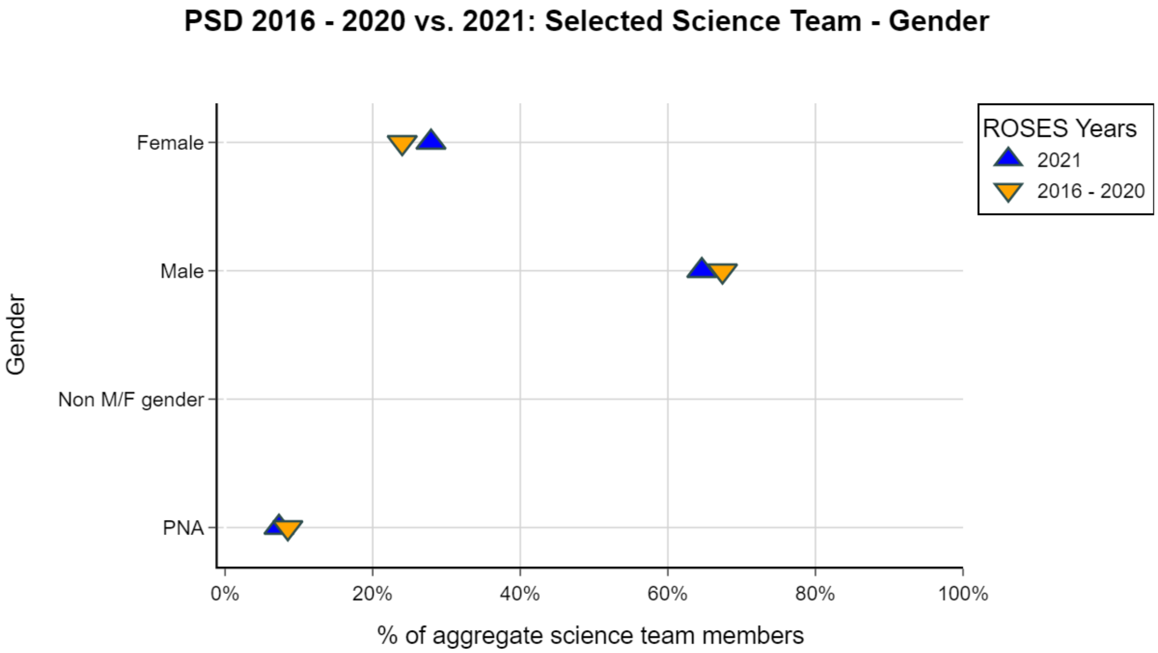
PSD Science Team: Submitted Gender - Data Table

PSD 2016 - 2020 vs. 2021: Submitted Science Team - Gender

Gender	PSD 2016 - 2020	PSD 2021
Female	24%	28%
Male	67%	64%
Non M/F gender	NR	NR
PNA	9%	8%

PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

PSD Science Team: Selected Gender - Plot



PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated.

Suppressed categories: Non M/F gender (All years).
See *Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics* for more information.

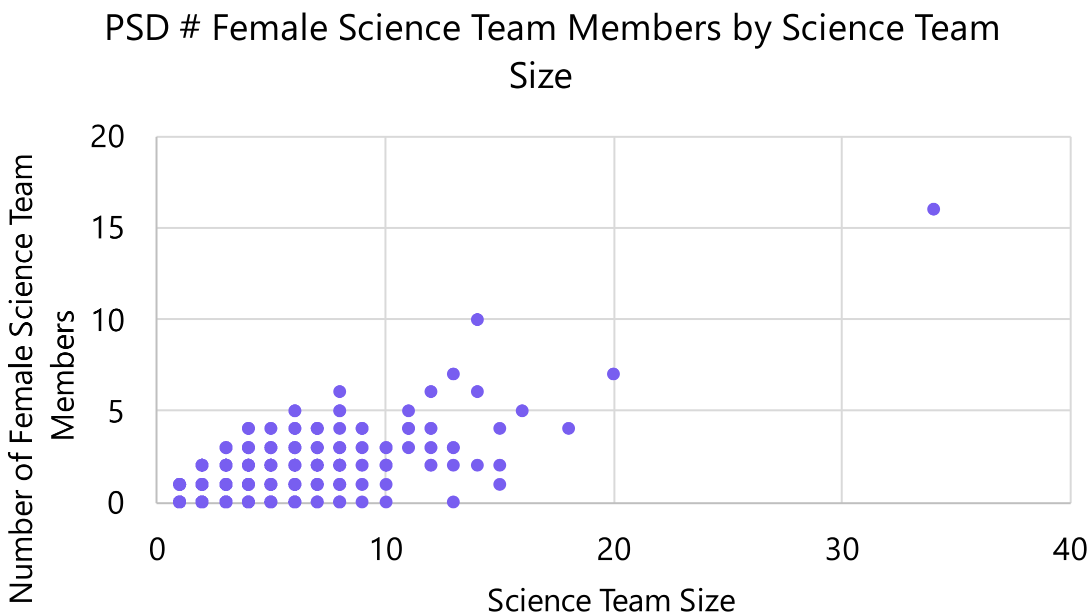
PSD Science Team: Selected Gender - Data Table

PSD 2016 - 2020 vs. 2021: Selected Science Team - Gender

Gender	PSD 2016 - 2020	PSD 2021
Female	24%	28%
Male	67%	65%
Non M/F gender	NR	NR
PNA	8%	7%

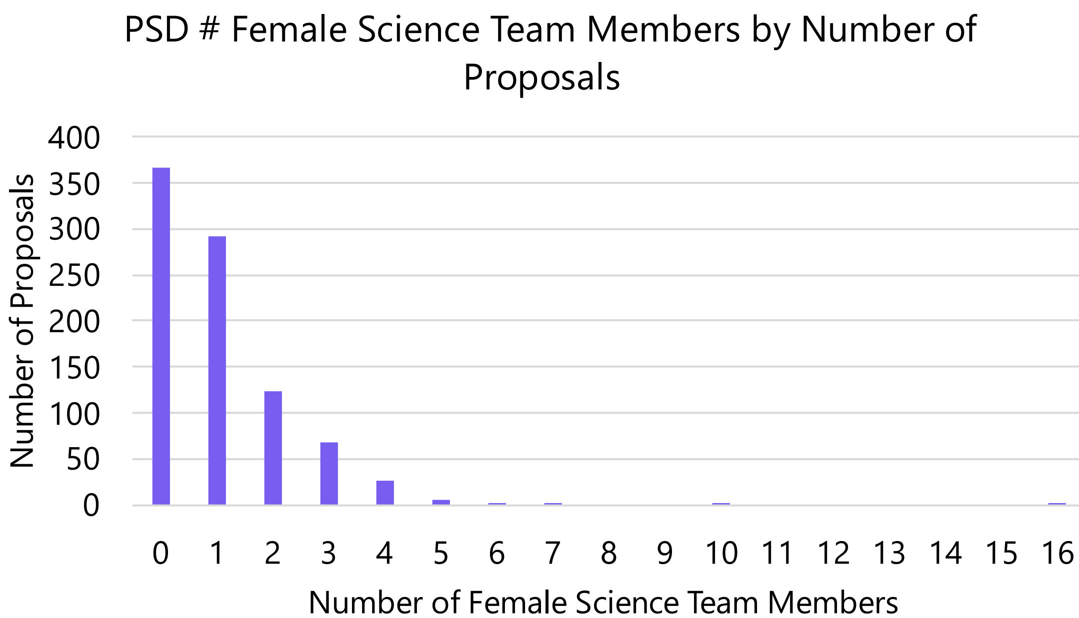
PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

PSD ROSES 2021 Science Teams: Number of Female Science Team Members by Science Team Size – Scatter Plot



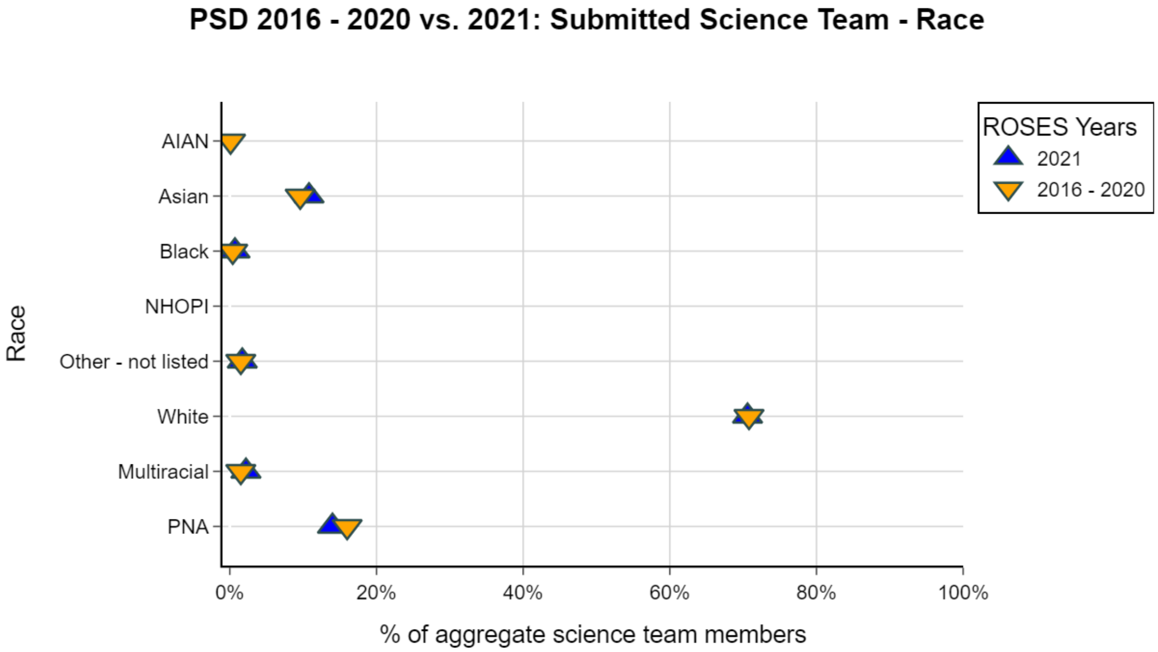
Note: 41% of proposals submitted to ROSES 2021 Planetary Science programs did not include female researchers in their science team. 24% of proposals submitted to ROSES 2021 Planetary Science programs only included the PI as the science team.

PSD ROSES 2021 Science Teams: Number of Female Science Team Members by Number of Proposals – Bar Chart



8.a.ii.3. Race – PSD Science team

PSD Science Team: Submitted Race - Plot



AIAN: American Indian and Alaska Native | NHOPI: Native Hawaiian and Other Pacific Islander | PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated.

Suppressed categories: AIAN (ROSES 2021), NHOPI (All years).
See *Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics* for more information.

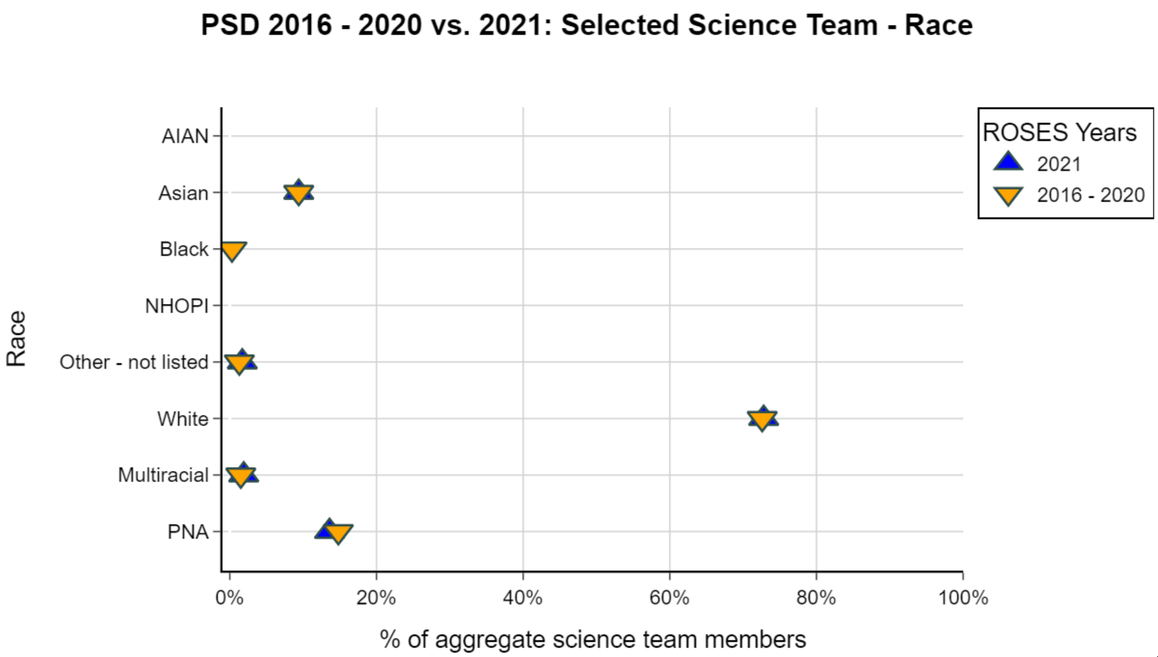
PSD Science Team: Submitted Race - Data Table

PSD 2016 - 2020 vs. 2021: Submitted Science Team - Race

Race	PSD 2016 - 2020	PSD 2021
AIAN	< 1%	NR
Asian	10%	11%
Black	< 1%	< 1%
NHOPI	NR	NR
Other - not listed	2%	2%
White	71%	71%
Multiracial	2%	2%
PNA	16%	14%

AIAN: American Indian and Alaska Native | NHOPI: Native Hawaiian and Other Pacific Islander | PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

PSD Science Team: Selected Race - Plot



AIAN: American Indian and Alaska Native | NHOPI: Native Hawaiian and Other Pacific Islander | PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated.

Suppressed categories: AIAN (All years), Black (ROSES 2021), NHOPI (All years).
See *Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics* for more information.

PSD Science Team: Selected Race - Data Table

PSD 2016 - 2020 vs. 2021: Selected Science Team - Race

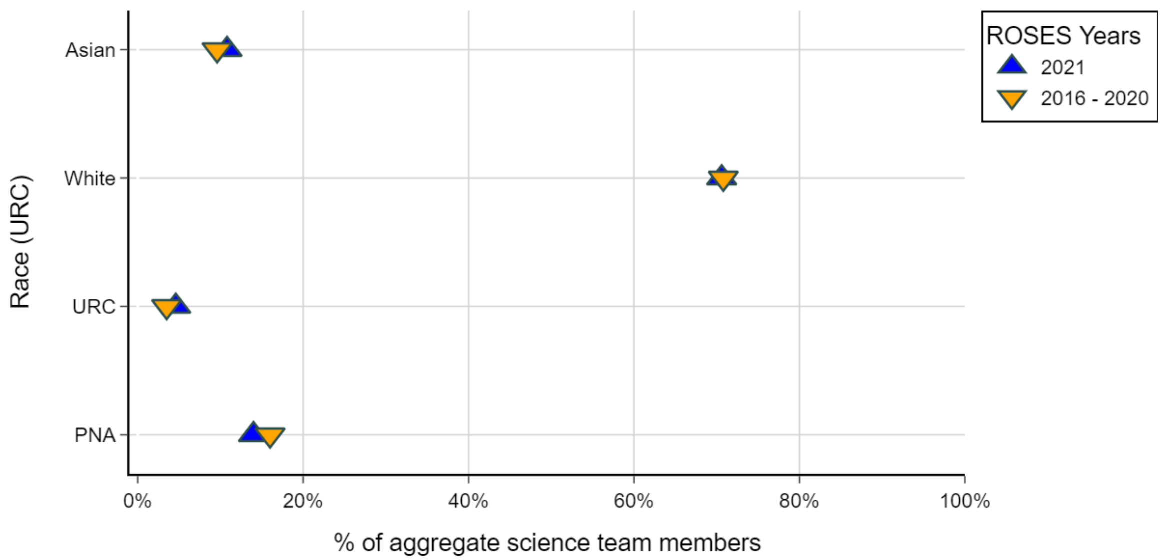
Race	PSD 2016 - 2020	PSD 2021
AIAN	NR	NR
Asian	9%	9%
Black	< 1%	NR
NHOPI	NR	NR
Other - not listed	1%	2%
White	73%	73%
Multiracial	2%	2%
PNA	15%	14%

AIAN: American Indian and Alaska Native | NHOPI: Native Hawaiian and Other Pacific Islander | PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

8.a.ii.4. Race using Under-Represented Community (URC) – PSD Science team

PSD Science Team: Submitted Race (URC) - Plot

PSD 2016 - 2020 vs. 2021: Submitted Science Team - Race (URC)



Under-Represented Community (URC) includes American Indian & Alaska Native, Black, Native Hawaiian & Other Pacific Islander, Multiracial, and Other. | PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated.

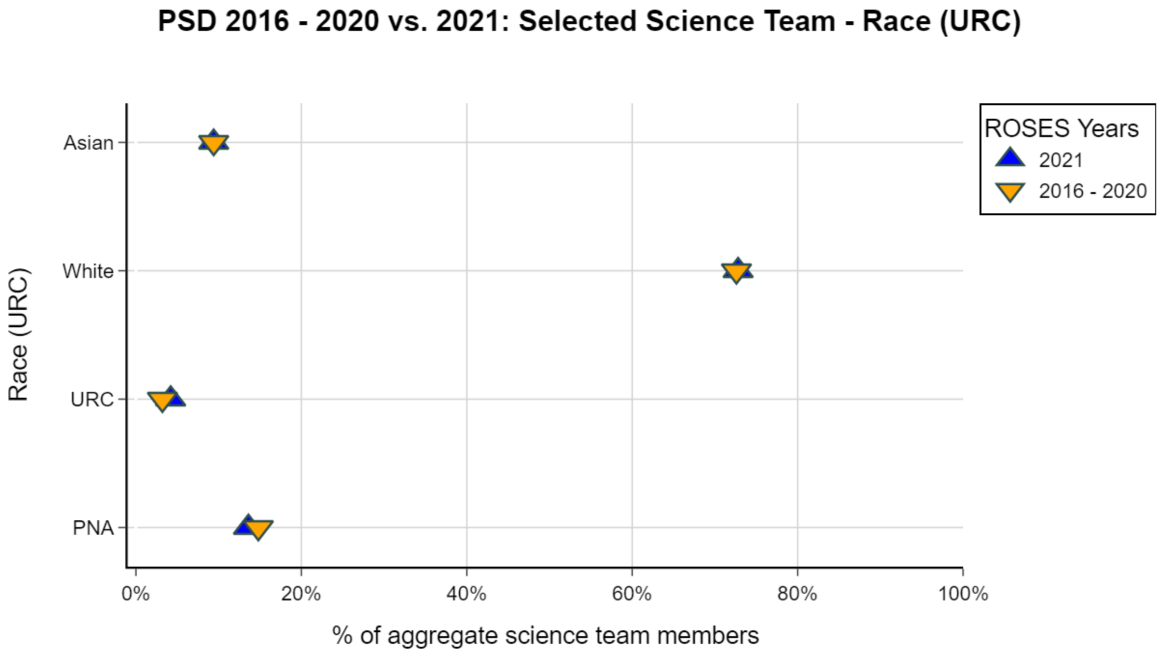
PSD Science Team: Submitted Race (URC) - Data Table

PSD 2016 - 2020 vs. 2021: Submitted Science Team - Race (URC)

Race (URC)	PSD 2016 - 2020	PSD 2021
Asian	10%	11%
White	71%	71%
URC	4%	5%
PNA	16%	14%

Under-Represented Community (URC) includes American Indian & Alaska Native, Black, Native Hawaiian & Other Pacific Islander, Multiracial, and Other. | PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

PSD Science Team: Selected Race (URC) - Plot



Under-Represented Community (URC) includes American Indian & Alaska Native, Black, Native Hawaiian & Other Pacific Islander, Multiracial, and Other. | PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated.

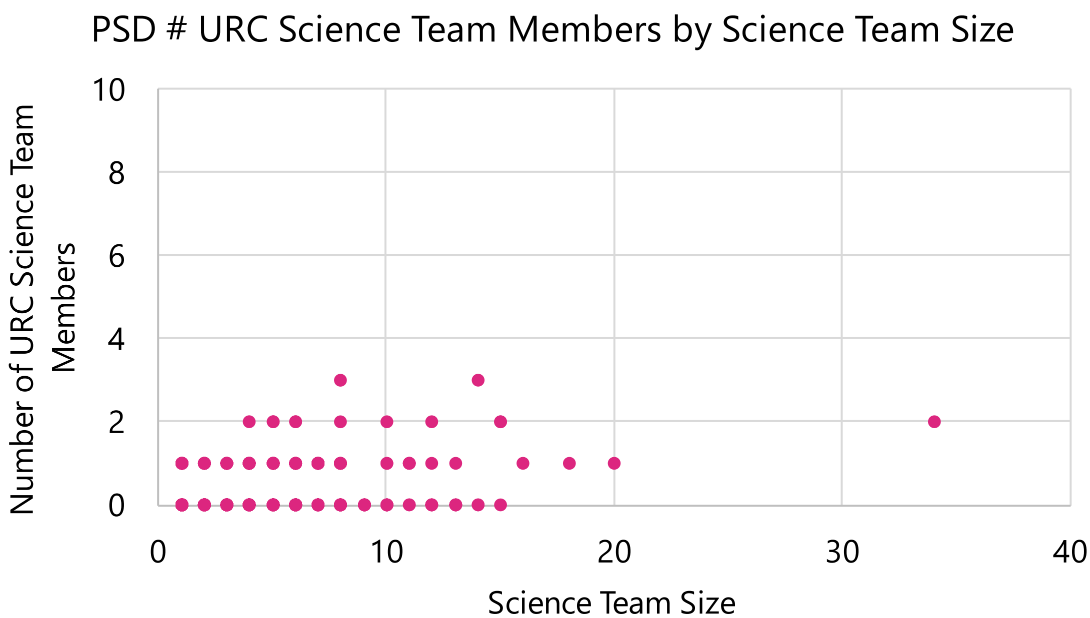
PSD Science Team: Selected Race (URC) - Data Table

PSD 2016 - 2020 vs. 2021: Selected Science Team - Race (URC)

Race (URC)	PSD 2016 - 2020	PSD 2021
Asian	9%	9%
White	73%	73%
URC	3%	4%
PNA	15%	14%

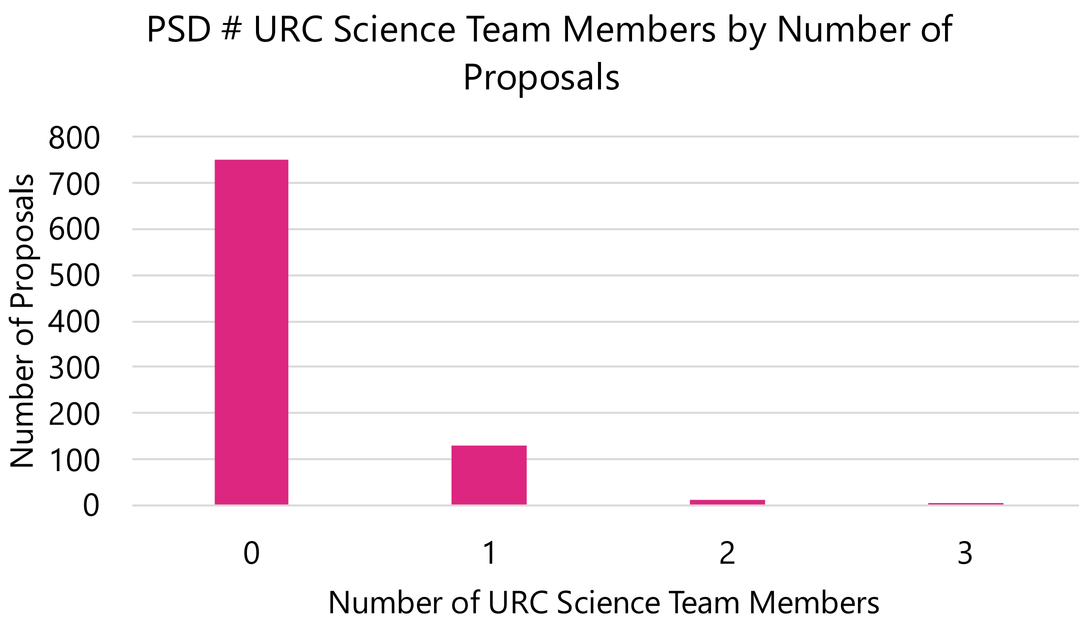
Under-Represented Community (URC) includes American Indian & Alaska Native, Black, Native Hawaiian & Other Pacific Islander, Multiracial, and Other. | PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

PSD ROSES 2021 Science Teams: Number of URC Science Team Members by Science Team Size – Scatter Plot



Under-Represented Community (URC) includes American Indian & Alaska Native, Black, Native Hawaiian & Other Pacific Islander, Multiracial, Other. | Note: 84% of proposals submitted to ROSES 2021 Planetary Science programs did not include URC researchers in their science team. 24% of proposals submitted to ROSES 2021 Planetary Science programs only included the PI as the science team.

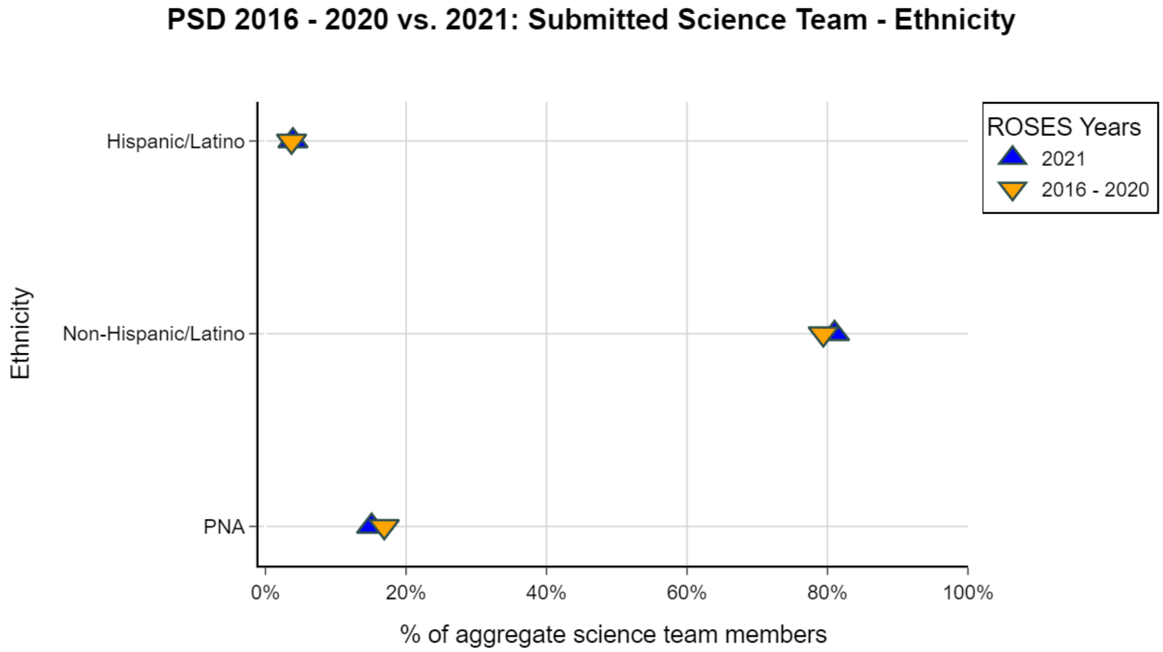
PSD ROSES 2021 Science Teams: Number of URC Science Team Members by Number of Proposals – Bar Chart



Under-Represented Community (URC) includes American Indian & Alaska Native, Black, Native Hawaiian & Other Pacific Islander, Multiracial, and Other.

8.a.ii.5. Ethnicity – PSD Science team

PSD Science Team: Submitted Ethnicity - Plot



PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated.

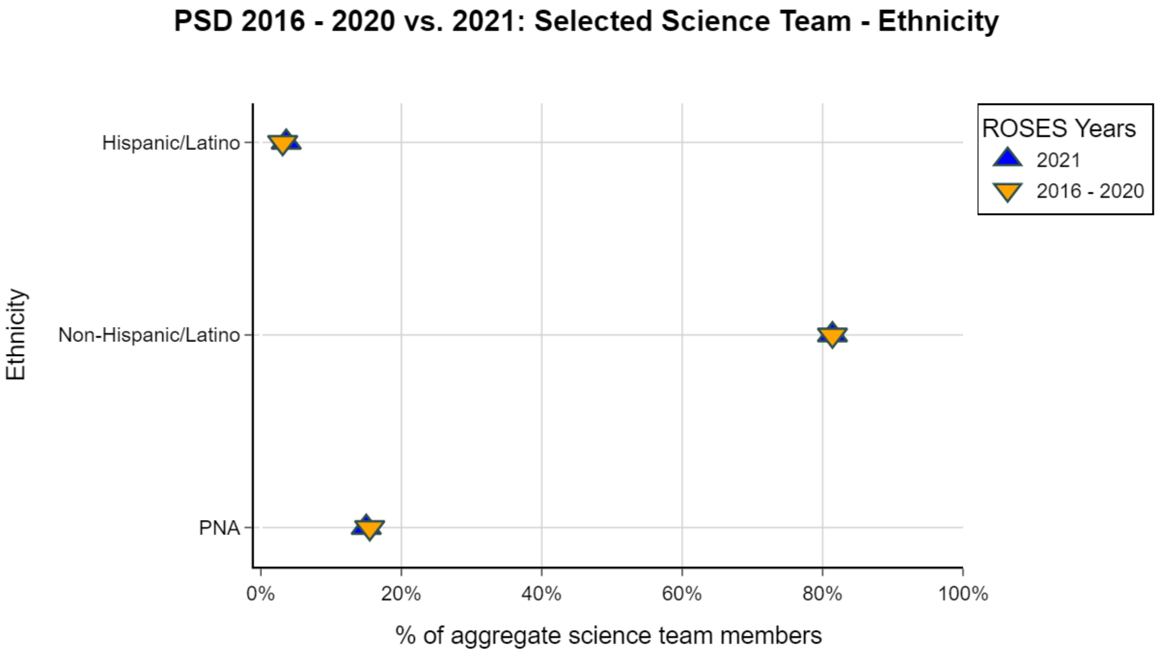
PSD Science Team: Submitted Ethnicity - Data Table

PSD 2016 - 2020 vs. 2021: Submitted Science Team - Ethnicity

Ethnicity	PSD 2016 - 2020	PSD 2021
Hispanic/Latino	4%	4%
Non-Hispanic/Latino	79%	81%
PNA	17%	15%

PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

PSD Science Team: Selected Ethnicity - Plot



PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated.

PSD Science Team: Selected Ethnicity - Data Table

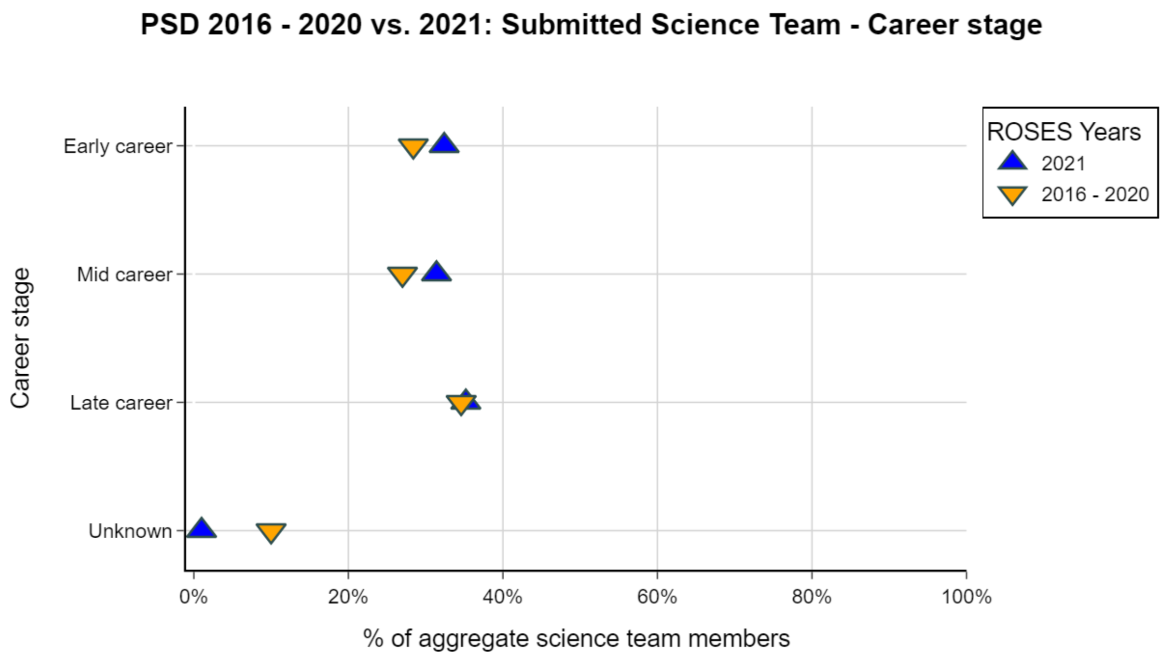
PSD 2016 - 2020 vs. 2021: Selected Science Team - Ethnicity

Ethnicity	PSD 2016 - 2020	PSD 2021
Hispanic/Latino	3%	4%
Non-Hispanic/Latino	81%	81%
PNA	16%	15%

PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

8.a.ii.6. Career Stage – PSD Science team

PSD Science Team: Submitted Career Stage - Plot



Early career: < 10 years since earning final degree | Mid career: 10 - 19 years since earning final degree | Late career: 20+ years since earning final degree | ROSES 2016-2020 proposal data are aggregated.

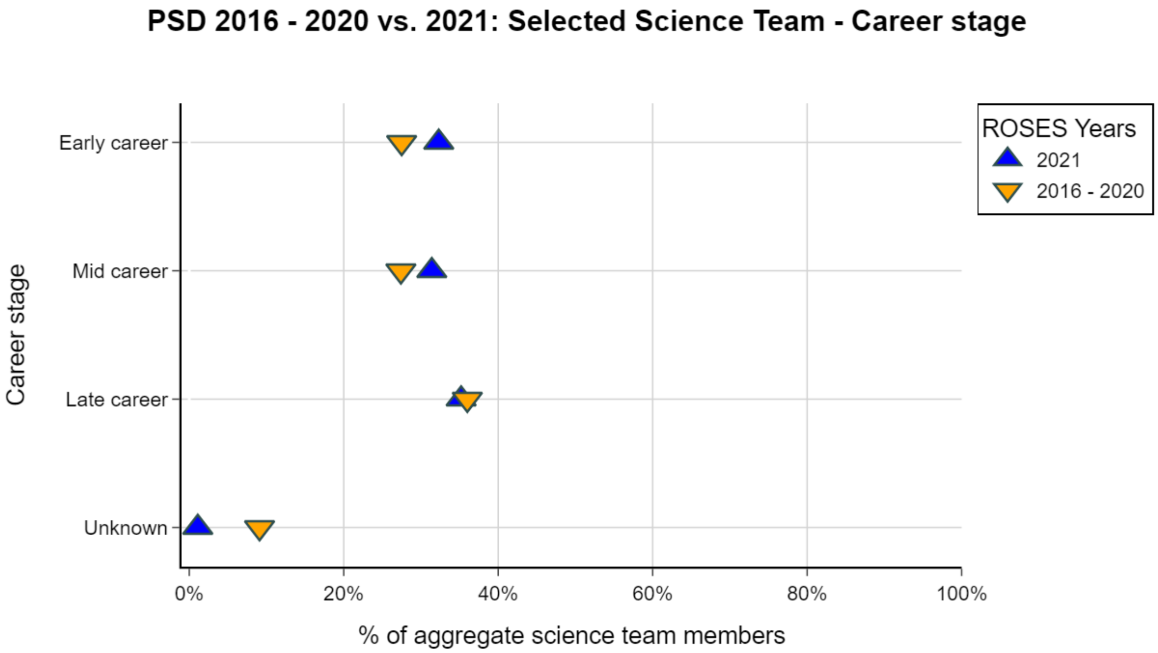
PSD Science Team: Submitted Career Stage - Data Table

PSD 2016 - 2020 vs. 2021: Submitted Science Team - Career stage

Career stage	PSD 2016 - 2020	PSD 2021
Early career	28%	32%
Mid career	27%	31%
Late career	35%	35%
Unknown	10%	1%

Early career: < 10 years since earning final degree | Mid career: 10 - 19 years since earning final degree | Late career: 20+ years since earning final degree | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

PSD Science Team: Selected Career Stage - Plot



Early career: < 10 years since earning final degree | Mid career: 10 - 19 years since earning final degree | Late career: 20+ years since earning final degree | ROSES 2016-2020 proposal data are aggregated.

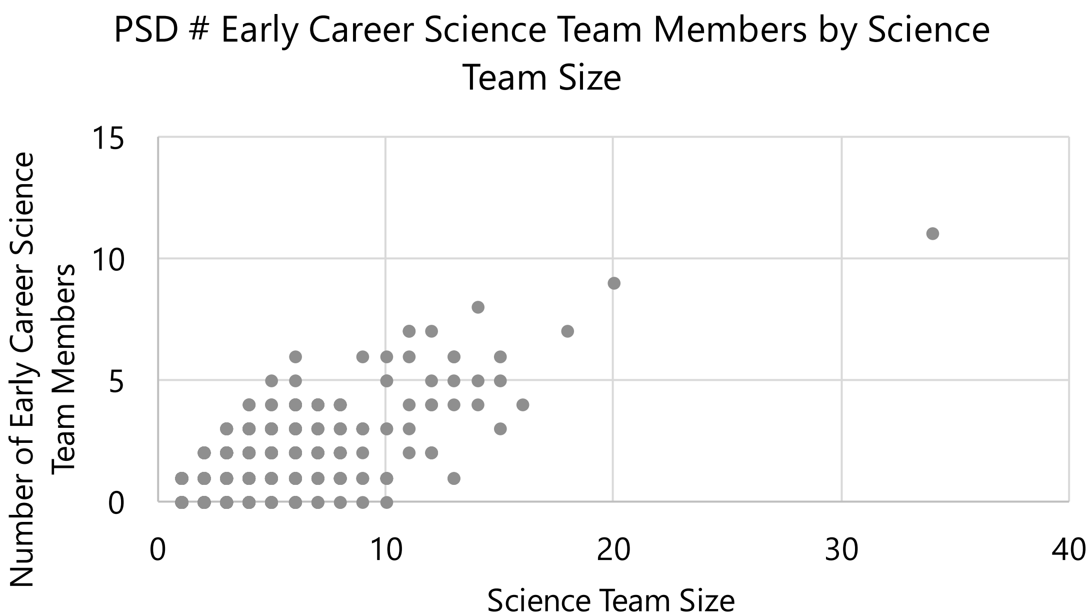
PSD Science Team: Selected Career Stage - Data Table

PSD 2016 - 2020 vs. 2021: Selected Science Team - Career stage

Career stage	PSD 2016 - 2020	PSD 2021
Early career	28%	32%
Mid career	27%	31%
Late career	36%	35%
Unknown	9%	1%

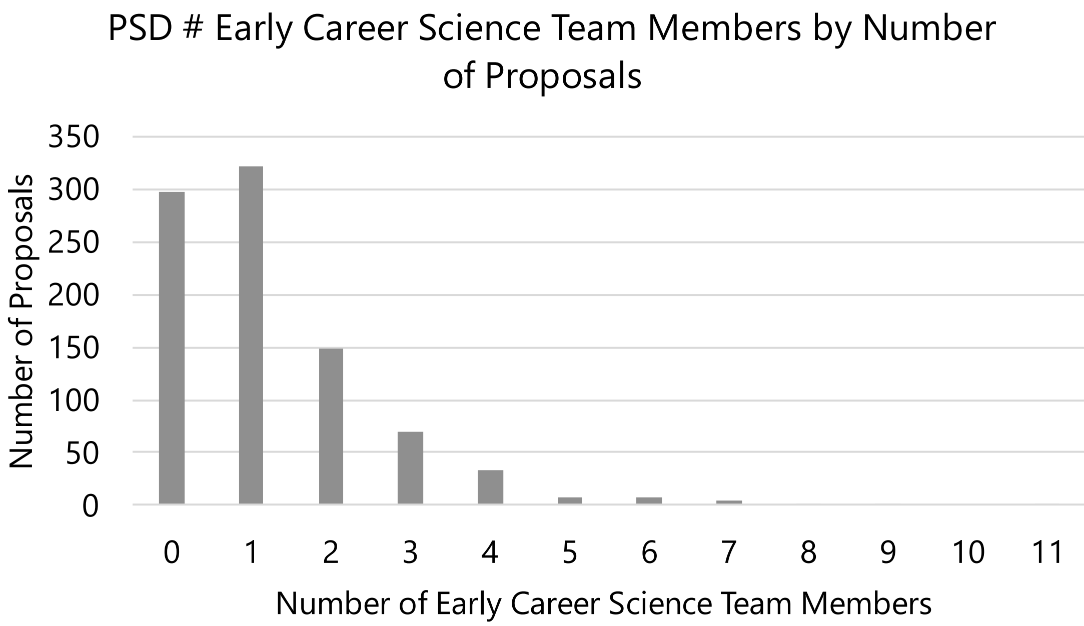
Early career: < 10 years since earning final degree | Mid career: 10 - 19 years since earning final degree | Late career: 20+ years since earning final degree | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

PSD ROSES 2021 Science Teams: Number of Early Career Science Team Members by Science Team Size – Scatter Plot



Early career: < 10 years since earning final degree | Note: 33% of proposals submitted to ROSES 2021 Planetary Science programs did not include early career researchers in their science team. 24% of proposals submitted to ROSES 2021 Planetary Science programs only included the PI as the science team.

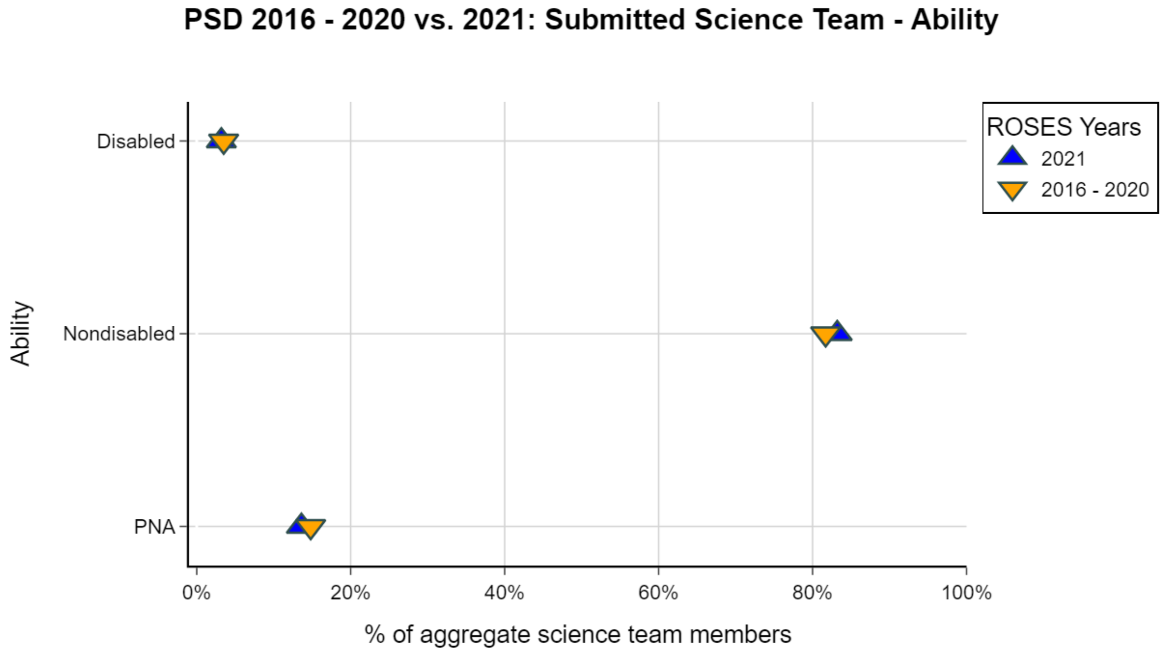
PSD ROSES 2021 Science Teams: Number of Early Career Science Team Members by Number of Proposals – Bar Chart



Early career: < 10 years since earning final degree

8.a.ii.7. Disability Status – PSD Science team

PSD Science Team: Submitted Ability - Plot



Disabled includes hearing, visual, mobility/orthopedic, and other impairment. | PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated.

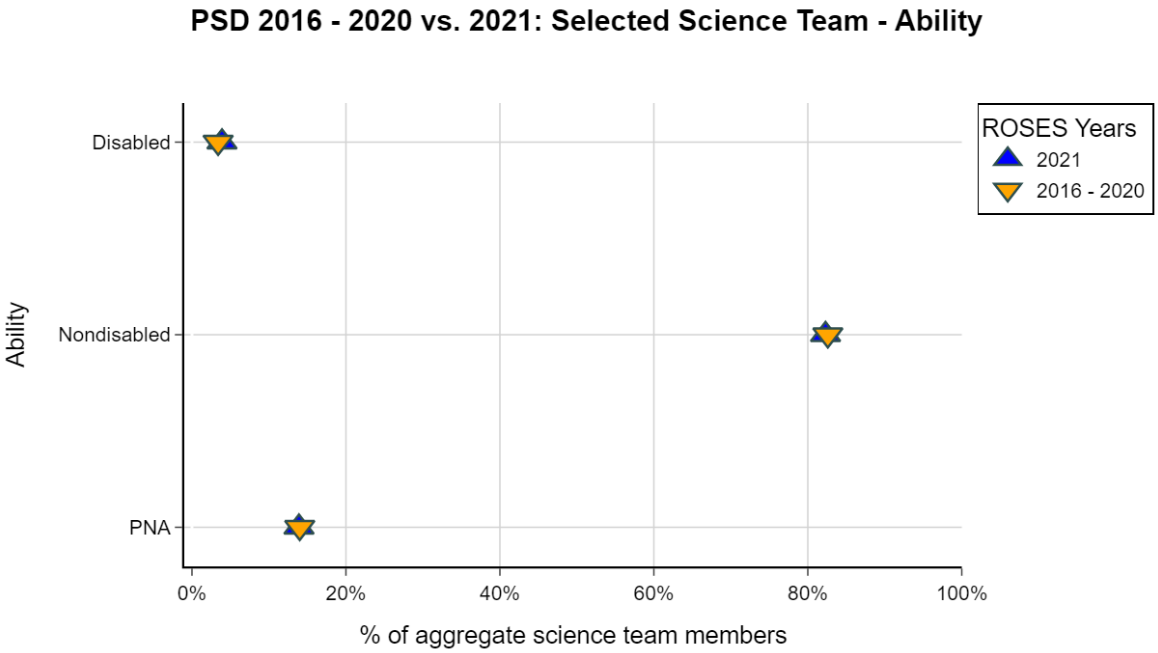
PSD Science Team: Submitted Ability - Data Table

PSD 2016 - 2020 vs. 2021: Submitted Science Team - Ability

Ability	PSD 2016 - 2020	PSD 2021
Disabled	4%	3%
Nondisabled	82%	83%
PNA	15%	14%

Disabled includes hearing, visual, mobility/orthopedic, and other impairment. | PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

PSD Science Team: Selected Ability - Plot



Disabled includes hearing, visual, mobility/orthopedic, and other impairment. | PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated.

PSD Science Team: Selected Ability - Data Table

PSD 2016 - 2020 vs. 2021: Selected Science Team - Ability

Ability	PSD 2016 - 2020	PSD 2021
Disabled	3%	4%
Nondisabled	83%	82%
PNA	14%	14%

Disabled includes hearing, visual, mobility/orthopedic, and other impairment. | PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

8.b. Proposal Data

8.b.i. New PIs

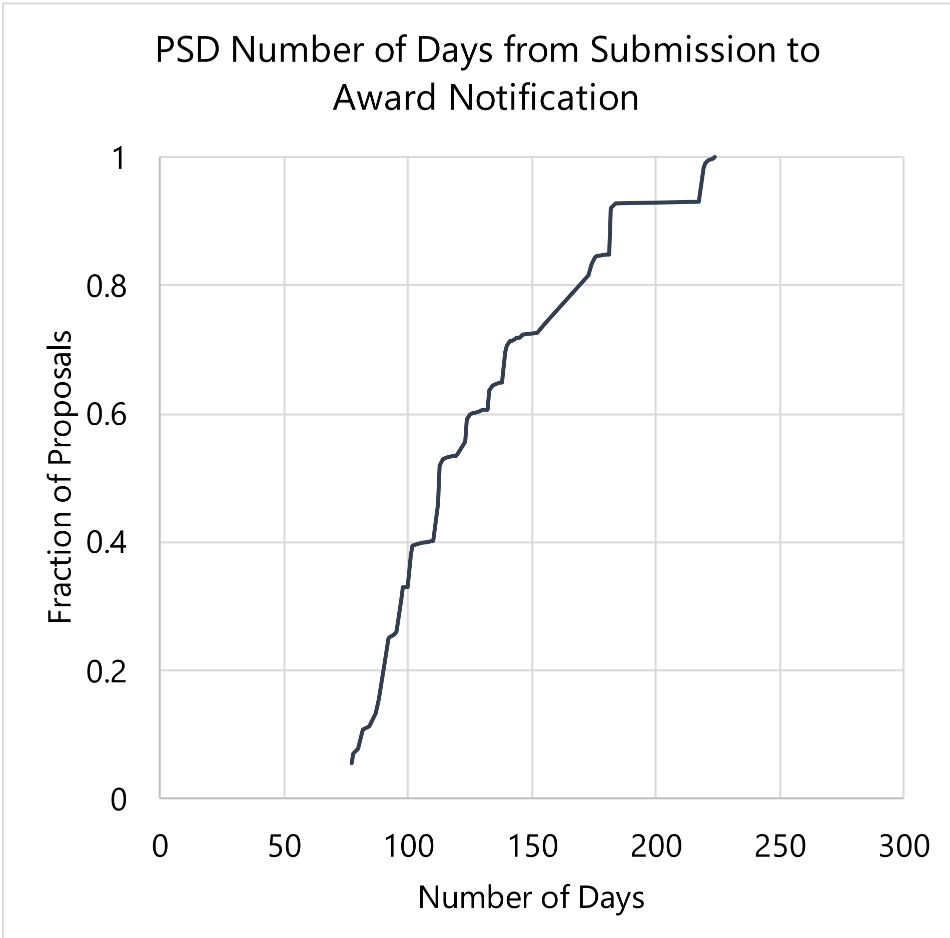
Comparison of Proposal Statistics of New PIs and Unique PIs for ROSES 2021

PSD 2021	New PIs	Unique PIs	New PI %
Selected	106	236	45%
Submitted	384	685	56%
Selection Rate	28%	34%	

New PI (Division): A PI that was selected by any program in the given SMD Division in ROSES 2021 but was not selected by any program in that SMD Division in the previous five ROSES years.
New PIs Submitted: an individual submitting a proposal that would be a new PI if the submitted proposal were selected.
Unique PIs: participation of individuals and not proposals.

8.b.ii. Time from Proposal Submission to Award Notification

Number of Days from Proposal Submission to Award Notification for PSD - Empirical Distribution Function



Notes: Number of days from proposal submission to 80% of award notifications for PSD is 173 days. SMD Policy Document SPD-22A applied to proposals submitted to ROSES 2016-2021 and included this statement: "Proposers shall receive a status notification from the Program Officer concerning their proposal no later than 150 days after the proposal due date, if selections have not yet already been made and announced."

Programs with no due dates not included: Emerging Worlds; Exobiology; Laboratory Analysis of Returned Samples; Planetary Data Archiving, Restoration and Tools; Planetary Instrument Concepts for the Advancement of Solar System Observations; Solar System Observations; Solar System Workings

8.c. ROSES 2021 Selection Announcements

Appendix C. Planetary Science Division

Appendix	Program Element Name
C.2	Emerging Worlds
C.3	Solar System Workings
C.4	Planetary Data Archiving, Restoration, and Tools
C.5	Exobiology
C.6	Solar System Observations
C.7	New Frontiers Data Analysis Program
C.8	Lunar Data Analysis
C.9	Mars Data Analysis
C.10	Cassini Data Analysis Program
C.11	Discovery Data Analysis
C.12	Planetary Instrument Concepts for the Advancement of Solar System Observations
C.14	Planetary Science and Technology Through Analog Research
C.15	Planetary Protection Research
C.16	Laboratory Analysis of Returned Samples
C.19	Planetary Science Early Career Award
C.20	Development and Advancement of Lunar Instrumentation
C.21	Hot Operating Temperature Technology
C.23	Yearly Opportunities for Research in Planetary Defense

C.25	Juno Participating Scientist Program
C.26	EnVision VenSAR Science Team
C.27	VIPER Mission Co-Investigator Program
C.28	Mars Science Laboratory Participating Scientist program
C.29	Analog Activities to Support Artemis Lunar Operations
C.30	OSIRIS-REx Sample Analysis Participating Scientist Program

Emerging Worlds
Abstracts of Selected Proposals
(NNH21DA001N-EW21)

Below are the abstracts of proposals selected for funding for the Emerging Worlds program. Principal Investigator (PI) name, institution, and proposal title are also included. 36 proposals were received in response to this opportunity. As of August 22, 2022 11 proposals were selected for funding. This concludes current selections under EW21.

Sachiko Amari/Washington University
Presolar graphite in CM chondrites

We propose to investigate various aspects of presolar graphite grains in CM chondrites. Presolar grains exhibit a range of density. It is believed that low-density graphite grains (1.6 2.1 g/cm3) formed in supernovae (SNe) and high-density graphite grains (2.1 2.2 g/cm3) formed in low-metallicity asymptotic giant branch (AGB) stars.

Proposed work 1: We will investigate organic molecules formed in SNe and low-metallicity AGB stars through analyses of organic molecules in low-density and high-density grains, respectively. Organic molecules formed in SN ejecta have not been observed. Organic molecules form C-rich AGB stars cannot be observed because the photospheric temperatures of the stars are too low to excite organic molecules. Detecting organic molecules in high-density graphite grains are the only way to learn what kind of organic phases formed during the AGB phase.
We will use microprobe two-step laser mass spectrometry at JSC, a unique instrument to analyze organic molecules in graphite grains. The essential feature of this instrument is that the molecule-specific 12C/13C ratios (= the 12C/13C ratios of particular types of molecules) can be obtained. If molecule-specific 12C/13C ratios are close to normal, we consider the organic molecules originated from the meteorite or from the lab. Since graphite grains with normal 12C/13C ratios are likely to contain organic molecules of normal 12C/13C ratios, we will focus on graphite grains with highly anomalous 12C/13C ratios. If 12C/13C ratios of organic molecules agree with those of the host graphite grains, it proves that the organic molecules formed in the same environment as the host graphite grains and are of stellar origin. If we succeed, it will be the first identification of organic molecules produced in SNe and C-rich AGB stars.

Proposed work 2: We will investigate isotopic ratios of heavy elements in graphite grains with LION, a new, improved resonance ion mass spectrometer at LLNL. Isotopic signatures of heavy elements are indicative of nucleosynthetic conditions in stars. Analyses of low-density graphite grains, which have never been done before, will provide us the conditions of nucleosynthetic processes in supernovae. Analyses of high-density graphite grains will give us information about the s-process conditions in lowest-metalliciy AGB stars that cannot be obtained by any other types of presolar grains.

Proposed work 3: We will analyze He and Ne in graphite grains to investigate nucleosynthesis in supernovae and stellar environments in supernovae and low-metallicity AGB stars. Abundant 22Ne-rich SN grains from 22Na are indicative of explosive H burning which might occur in the outer SN zone. Ion implantation also takes place in supernova ejecta. Grains with 20,21Ne indicate that those grains formed in different SN environments where Ne was implanted. When we combine the results from Proposed work 2 and 3, we will better understand the dynamics of SNe.
Ion implantation is the only way to acquire noble gases in AGB stars. Since there are only a few gas-rich grains of AGB star origin, more data are needed to shed light on how the light noble gases were acquired into presolar grains during the last stage of stellar evolution.

Presolar dust is the window to probe nucleosynthesis in stars, mixing in the stellar ejecta, and the dynamics in stars. Supernovae and AGB stars, the main stellar sources of presolar graphite, synthesized elements that eventually made the solar system. We will be able to obtain a better insight into nucleosynthesis in those stars through analyses of graphite grains. Organic phases are another building block of the solar system. We know very little how organic phases are synthesized in the stellar outflow. The investigations described here are in line with one of the scopes of the Emerging Worlds program, where studies of the materials present and processes that led to the onset of Solar System formation" are encouraged.

Maitrayee Bose/Arizona State University
An Integrated Experimental and Theoretical Approach to Study Presolar Grains

Objectives: The study of presolar grains in primitive meteorites is fundamental to understanding both the building blocks of our
Solar System and the stars in the pre-solar-system environment. Since their discovery, numerous studies of presolar dust grains
have provided information on the types of stellar sources that contributed to the protosolar nebula, the environments in which they
condensed, their processing in the protoplanetary disk, and possible secondary alteration processes subsequent to asteroid formation. However, several unanswered questions remain: Can very low carbon and nitrogen isotope ratios in SiC grains be produced in supernova ejecta? Are novae important contributors to the presolar grain inventory? We propose a coordinated laboratory and modeling study that will help elucidate these questions and yield an unprecedented understanding of grain condensation in stellar explosions.

Plan: We propose to measure isotopes of Li, Mg, Ca, and Ti in rare presolar grains because of the following reasons:
(1) Lithium can be produced in a variety of settings including irradiation of high energy particles released from solar flares that
collided with solar nebula oxygen gas and neutrino interactions in a supernova. Recently, Co-I Starrfield developed new carbon-oxygen nova models that agree with observations of recent nova outbursts and predict carbon, nitrogen, silicon, aluminum, and sulfur

isotope compositions of SiC grains. These same models also predict that classical carbon-oxygen novae produce copious amounts of 7Be that decays to 7Li (half-life 53 days) similar to that observed in such explosions in our galaxy. Thus, nova condensates should show extremely large 7Li/6Li ratios, which can be orders of magnitude larger than observed in mainstream SiC grains (7Li/6Li = 9-13). Our plan is to measure Li isotopes in nova candidate grains with carbon and oxygen-anomalous compositions and to use lithium as a tracer to distinguish nova grains from other grain types. We will also evaluate the output of several carbon-oxygen and oxygen-neon models by changing numerous parameters, aimed at describing current nova
observations.
(2) To date, one-dimensional core-collapse supernova modeling has been used to understand the origins of SiC grains by ad-hoc mixing of material from different zones of a supernova. However, there is no physical basis for this assumed large-scale microscopic mixing. Recently, Co-I Young produced several three-dimensional core-collapse supernova models that included hydrodynamic instabilities, post-explosion convection, and global asymmetries to understand the supernova remnant Cassiopeia A. These models are an excellent fit to the SiC grain compositions, including those with very low 12C/13C and 14N/15N ratios. Our plan is to perform isotopic measurements of key elements (Mg, Al, Ca, and Ti) in presolar SiC, silicate and oxide grains of supernova origin to compare to these novel core-collapse supernova models. In addition, we will test new low-mass (8-15 M□) supernova progenitors, progenitor convection-driven asymmetries, and estimate production of lithium by spallation in the supernova ejecta.

Methods and Samples: The PI will carry out the proposed isotopic work in presolar grains from a suite of meteorites using the
NanoSIMS. Co-Is Starrfield and Young will provide new nova and supernova models aimed at understanding the kinetics and
nucleosynthesis in stellar explosions.

Significance: The research proposed will aid in our understanding of the nova and supernova parent stars of presolar grains. The models proposed to replicate real-time stellar explosions, in concert with the proposed isotopic measurements, will allow us to understand & materials (presolar) present and processes that led to the onset of Solar System formation". The proposed research, therefore, is highly relevant to the goals of Emerging Worlds solicitation.

Greg Brennecka/Lawrence Livermore National Laboratory/Dept of Energy
Reconstructing the Primordial Architecture of the Solar System

Proposal title: Reconstructing the primordial architecture of the Solar System
P.I.: Gregory Brennecka
P.I. Institution: Lawrence Livermore National Laboratory (LLNL)

Goal: The asteroid belt is an assemblage of planetary debris located between the orbits of Mars and Jupiter that contains material formed over a large range of distances from the Sun. The belt was formed by the ancient migrations of the gas giants disrupting the original structure of the Solar System, placing disparate materials from the inner and outer Solar System into a relatively narrow band orbiting the Sun. The goal of this study is to use various meteoritic materials sourced from the asteroid belt to broadly reconstruct the architecture of the Solar System prior to the migration of the gas giants. Specifically, isotopic signatures of nucleosynthetic origin from multiple elements will be used to cosmolocate" the feeding zones of various meteoritic materials. This project is divided into 3 tasks:

Task 1: Identifying planetary feeding zones using nucleosynthetic anomalies. This task proposes to investigate a wide variety of meteoritic samples thought to represent inner and outer regions of the early Solar System, applying high-precision isotope analyses to a comprehensive set of elements with variable geo- and cosmochemical behavior. In particular, elements heavier than Ni (e.g., Zr, Mo, Nd, Sm, and Hf) will be used to obtain insights into the presolar heritage of elements in the Solar System, because nuclides of these elements are produced exclusively by the three main nucleosynthetic production pathways, (s-, r-, and p-processes). Integrating isotopic signatures from multiple elements of the same samples will likely uniquely define the stellar environments that caused these certain isotopic variations.

Task 2: Chronologically constrain nucleosynthetic signatures. The objective of Task 2 is to integrate high precision chronologic investigations into studies of nucleosynthetic anomalies obtained in previous studies and those from Task 1. This will determine how the nucleosynthetic source of elements changed throughout the earliest period of Solar System evolution. The age of individual samples will be determined using a variety of chronometers, including 26Al-26Mg, 53Mn-53Cr, and U-Pb, that are currently in use at LLNL. By comparing the measured ages with the nucleosynthetic signatures observed in various types of meteoritic samples, the compositional evolution of the proto-planetary disk will be constrained.

Task 3: Identifying the carriers of nucleosynthetic anomalies. The goal of this task is to evaluate the isotopic signatures of various individual components contained within undifferentiated meteorites to determine the primary carriers of nucleosynthetic anomalies. This will involve analysis of microscopic phases such as presolar grains previously known to be extraordinary in their isotopic compositions. This work will utilize the nanoSIMS and RIMS capabilities and expertise at LLNL to determine if isotopically anomalous components can be tied to bulk scale isotopic anomalies measured as part of Task 1.

Relevance: The work proposed here is relevant to the Emerging Worlds Program because it is focused on the materials that contributed to the formation of planets, satellites, and minor bodies in the Solar System. The tasks designated here will constrain: 1) the isotopic composition of the materials that formed various Solar System bodies, 2) the isotopic structure of the Solar System at the time of disk formation, and 3) the timeframes associated with early Solar System formation and dynamics.

Jangmi Han/University Of Houston
Coordinated Microanalyses of Refractory Inclusions and Insights into Their Condensation Origin

Pristine fine-grained, spinel-rich Ca, Al-rich inclusions (FGIs) in carbonaceous chondrites are among the first solids to form in the early Solar System and are widely interpreted as aggregates of direct high-temperature condensates from a cooling nebular gas. Studies of FGIs provide crucial information on early high-temperature environments in the solar nebula and how the first Solar System solids formed, evolved, and migrated within the protoplanetary disk. We propose a coordinated microstructural, mineralogical, and isotopic study of FGIs from reduced CV3 chondrites to better understand their origin and nature, and ultimately, high-temperature condensation conditions and processes in the early solar nebula.

In Task 1, we will use focused ion beam/transmission electron microscopy (FIB/TEM) techniques to determine the micro-to-nanometer scale mineralogy, petrography, chemical compositions, and microstructures of FGIs and their surrounding matrix from reduced CV3 chondrites. A major objective of this work is to resolve long-standing questions regarding the discrepancies between thermodynamic models, petrologic observations, and kinetic effects on nebular condensation sequences and processes. Given their fine-grained nature, FGIs are susceptible to parent body alteration processes that can obscure or overprint the record of primary nebular events. To ensure that our mineralogical, chemical, and isotopic measurements of FGIs represent primordial nebular signatures, not parent body modifications or overprinting, we will perform FIB/TEM analyses of fine-grained matrix from these chondrites to quantify the degree and extent of secondary parent body alteration.

In Task 2, we will obtain coordinated in situ oxygen isotopic analyses and Al-Mg chronology using NanoSIMS and SIMS of FGIs from reduced CV3 chondrites in order to constrain the isotopic evolution of nebular gas reservoirs in the early solar nebula. Importantly, we will seek for any evidence for oxygen isotopic heterogeneity that may reflect a transport between nebular gas reservoirs with different oxygen isotopic compositions. We will measure the Al-Mg isotope systematics to determine the relative chronology and timescales of dust condensation and aggregation to form larger FGIs in the early solar nebula.

The proposed research on FGIs and matrix in reduced CV3 chondrites is directly relevant to the scientific goal of the Emerging Worlds program to understand the formation of our Solar System". The research will enable a more complete understanding of high-temperature condensation processes and conditions in the early solar nebula, as the first steps to form solids during the Solar System formation.

Alexander Krot/University of Hawaii, Honolulu

Isotopic evolution of protoplanetary disk recorded by refractory inclusions and chondrules in CH and CB carbonaceous chondrites

The genetically related CH and CB chondrites contain various proportions of multiple generations of chondrules and Ca,Al-rich inclusions (CAIs) formed by different processes and at different times: 1. Typically 16O-rich (D17O ~ 240) CAIs which are surrounded by Wark-Lovering (WL) rims and formed by condensation±melting near the protosun at the beginning of the Solar System formation (t0). (2) Porphyritic chondrules that formed by melting, often incomplete, of solid precursors in the protoplanetary disk (PPD). (3) 16O-depleted (D17O ~ 15 to 70) igneous CAIs surrounded by the apparently igneous rims and non-porphyritic chondrules which crystallized from complete melts produced in an impact-generated plume ~4.5 Ma after t0. The CBs consist almost exclusively of the impact plume-produced components, whereas the CHs contain all three types of components (Krot et al. 2021).
We have recently shown that grossite-bearing CH and CB CAIs with WL rims have internally uniform O-isotope compositions, but exhibit a large inter-CAI range of D17O, from -400 to -50, providing a strong evidence for large variations in D17O of the nebular gas in the CH and CB CAI-forming region(s) (Krot et al. 2020). Because many previously measured grossite-bearing CH CAIs have low initial 26Al/27Al ratio [(26Al/27Al)0], <5x10-6 (Kimura et al. 1993; Weber et al. 1995; Krot et al. 2008, 2014a), we hypothesized that most grossite-bearing CH CAIs formed prior to the injection and homogenization of 26Al in the PPD at the canonical level (~5x10-5), and hence recorded a very early generation of isotopically distinct oxygen reservoirs in the disk. If correct, this suggests that isotopic heterogeneity of the major O-bearing species (CO, H2O, silicates) in the early Solar System was inherited from the protosolar molecular cloud (Krot et al. 2020). We note, however, that the coupled O- and Al-Mg isotope data for the CH and CB CAIs are virtually absent and signify a critical knowledge gap.
In order to understand the origin of D17O heterogeneity in the early Solar System, and the evolution of D17O and (26Al/27Al)0 in the PPD, we propose to measure in situ O and 26Al-26Mg systematics of amoeboid olivine aggregates (AOAs), mineralogically diverse CAIs (grossite-, hibonite-, melilite-, pyroxene-rich) surrounded by WL rims, and relict CAIs in porphyritic chondrules from CHs, CBs and Acfer 094 (C3.0) using ion microprobe (SIMS). The isotope measurements will be coordinated with analyses using scanning electron microscopy (SEM), cathodoluminescence (CL), electron backscattered diffraction (EBSD), electron probe microanalysis (EPMA), and focus ion beam (FIB)+scanning transmission electron microscopy (STEM). Electron energy loss spectroscopy (EELS) will be used to determine the oxidation state of Ti in fassaite, as a direct measure of fO2 of the nebular gas with which CAIs having different D17O equilibrated. We will explore two mechanisms of radial transport of CH CAIs of different generations and sizes   radial diffusion through disk mid-plane and disk wind.

In order to test a hypothesis that the 16O-depleted igneous CAIs surrounded by the apparently igneous rims in CBs and CHs formed by complete melting of pre-existing refractory inclusions followed by gas-melt interaction in impact plume (Krot et al. 2017a), we propose to study the mineralogy, petrography, O- and Mg-isotope compositions, and trace element abundances of these CAIs and their rims using SEM, CL, EPMA, EBSD, FIB +STEM, and SIMS. To estimate fO2 of the plume gas with which the 16O-depleted igneous CAIs equilibrated, we will determine the oxidation state of Ti in the CAI pyroxenes using EELS. The textures, mineralogy, chemical and isotopic compositions of these CAIs and their rims will be compared with igneous and non-igneous CAIs surrounded by WL rims in CH, CB, and other primitive chondrites.

Simone Marchi/Southwest Research Institute
Impact-driven accretion of Earth's C,H,N,S volatiles

The origin of Earth's volatile elements (notably, C, H, N, and S; hereinafter CHNS) permeates many different aspects of planetary sciences, with far-reaching implications spanning broad areas of research including dynamical evolution of the early Solar System, geochemistry of the solid Earth, and origin of life and astrobiological investigations. While so crucial to planetary sciences, the origin and abundances of early inventories of terrestrial CHNS remain debated.

The present terrestrial budget of CHNS elements is the result of the alteration of the proto-Earth by a Moon-forming giant impact (GI) and subsequent late accretion. In this proposal, we investigate CHNS accretion through planetesimal and embryos collisions to form the proto-Earth, and track CHNS delivery for a range of GI scenarios and late accretion histories.
Our proposed work uses three comprehensive Tasks to evaluate terrestrial CHNS delivery and mobilization via large-scale collisions of differentiated objects, including the complex, interrelated effects of impact delivery and mixing, planetesimal composition and internal partitioning, and current models of the GI and late accretion. We build on prior work by: using 3D impact simulations tailored for describing large oblique collisions and the differing retention of projectile core vs. mantle material by the bulk silicate Earth (Task 1); assessing the partitioning of CHNS within the proto-Earth, large planetary embryos responsible for the GI, and differentiated late accreting projectiles through thermodynamic calculations (Task 2), and modeling the cumulative effects of proposed bombardment histories from the GI through late accretion on the Earth's CHNS inventories for comparison with observed constraints (Task 3). Although we focus on the impact-driven delivery of CHNS for Earth, our work will also provide a framework for understanding volatile delivery in large collisions relevant to all rocky planets with protracted growth histories.

The proposed research focuses on the origin of terrestrial CHNS volatile and is relevant to many aspects of the research indicated in the Emerging World program. The outcome of our project is thus relevant to NASA's goals for Planetary Science and Earth Science. More broadly, processes investigated in this proposal are also relevant to other rocky planets (e.g., Venus, Mars, Mercury, and exoplanets).

David Nesvorny/Southwest Research Institute
Planetesimal Formation, Evolution, and Impacts

The proposed work consists of three themes related to the formation, evolution and impacts of planetesimals in the Solar System:

Theme 1: Planetesimal and Planetesimal Binary Formation
Planetesimals are compact astrophysical objects roughly 1-1000 km in size, massive enough to be held together by gravity. They are thought to form by complex physical processes from small grains in protoplanetary disks. The streaming instability (SI) model states that mm/cm-size particles (pebbles) are aerodynamically collected into self-gravitating clouds which then directly collapse into planetesimals. Here we analyze high-resolution simulations of SI to characterize the initial properties (e.g., rotation) of pebble clouds, and follow each cloud's collapse to completion with the PKDGRAV N-body code. The results will reveal how planetesimal and planetesimal binary properties depend on local disk conditions, and how observations of Kuiper Belt Objects (KBOs) and KBO binaries can be used to better understand planetesimal formation in the outer Solar System.

Theme 2: Scattered Disk Formation in the Stellar Cluster Environment
The Kuiper Belt, a diverse population of bodies beyond Neptune, represents an important constraint on the early evolution of the outer Solar System. The dynamical models that we helped to develop in the past decade can now accurately explain the orbital distribution of KBOs. They indicate that Neptune migrated on a modestly eccentric orbit. The existing dynamical models, however, fail to reproduce the relatively flat radial profile of Scattered Disk Objects (SDOs) at 50-200 au. Our preliminary tests show that this problem is most likely related to Sun's birth environment in a stellar cluster. We will conduct dynamical simulations of the Kuiper Belt formation to characterize the cluster effect in detail, and draw implications from this work for the cluster properties.

Theme 3: Formation of Lunar Basins from Impacts of Leftover Planetesimals
The lunar impact basins hold important clues to the early history of the inner Solar System. From the radiometric dating of Apollo samples we know that at least some basins, such as Imbrium, formed relatively late, 650 Myr after the first Solar System solids. We will construct early bombardment models of the terrestrial worlds to: (i) determine the relative contribution of various impactor populations (leftover planetesimals, asteroids, comets), (ii) constrain the number and radial profile of planetesimals in the terrestrial planet zone, and (iii) provide context for the interpretation of the lunar crater record. Per 2023-2032 Decadal Survey recommendations, understanding the early impact record in the inner Solar System is one of the chief NASA priorities in the next decade.

Relevance Statement

The proposed research is fundamental to understanding the formation and early evolution of the Solar System. This is a central theme of NASA's Strategic Goals and the Emerging Worlds program. Specifically, the NRA for the Emerging Worlds program states that the program "aims to answer the fundamental science question of how the Solar System formed and evolved", and that the program objectives include "formation, accretion, and evolution of Solar System bodies" and "early dynamical evolution of the Solar System". The types of studies that are supported include "theoretical studies". Here we propose theoretical investigations of the formation and early evolution of the Solar System. This includes planetesimal accretion processes, early dynamical evolution of planetesimals, and planetesimal impacts on the terrestrial worlds. These themes are directly relevant to the NASA Strategic Goals and Research Objectives, and to the Emerging Worlds program in particular. Our goal is to constrain planetary formation processes and the events that have taken place in the early Solar System.

Michel Nuevo/NASA Ames Research Center

Ultraviolet Photoprocessing of Ices and Organics in Space: The Effect of N2 and O2 Ices on the Formation of Meteoritic-Like Materials

Science Goals: Ices and organics in interstellar clouds and protostellar disks are exposed to UV photons and energetic particles. This process leads to the formation of new, complex organic molecules (COMs) and the alteration of existing ones, and may play an important role in the inventory of organics in primitive Solar System objects like asteroids and comets. Astronomical infrared (IR) observations show that astrophysical ices largely consist of simple molecules such as H_2O, CH_3OH, CO, CO_2, NH_3, CH_4, etc. However, indirect observations and chemical models suggest that these ices may also contain significant amounts of N_2 and O_2. The abundances N_2 and O_2 in ices are difficult to estimate because they have no dipole moment and therefore no IR signatures, but their expected abundances suggest that their contribution to ice chemistry and the formation of COMs may be important. We propose to perform laboratory studies of astrophysical ices that contain N_2 and/or O_2 to compare the chemical and elemental compositions of the organics formed during this process with (i) those made from ices that did not contain N_2 and O_2, and (ii) organics in extraterrestrial materials, mostly meteorites.

Photo-induced production and alteration of COMs: The UV irradiation of simple astrophysical ice analogs leads to the formation of residues consisting of complex organics such as amino acids and sugar derivatives. When small polycyclic aromatic hydrocarbons (PAHs) are added to the ices, functionalized PAHs and N- and O-heterocycles also form. Many of these organics are found in meteorites, suggesting that UV photochemistry could be an important source for their formation. Exposure of these organics to additional high-energy radiation (X-ray and hard UV photons) results in changes in their chemical composition; they become more aromatic and resemble meteoritic insoluble organic matter (IOM). We propose to study the production of COMs from the UV irradiation of similar ice mixtures that also contain N_2 and/or O_2 and compare their chemical composition with COMs produced ices that do not contain N_2 and O_2 and meteoritic organics.

Methodology: Ice mixtures consisting of H_2O, CH_3OH, CO, NH_3 that also contain N_2 and/or O_2, with and without small PAHs, will be exposed to UV irradiation at <20 K and subsequently warmed to room temperature. Relative proportions of N_2 and O_2 in the ices will span the abundance range inferred from observations and predicted by chemical models. Residues thus produced will be studied both before and after additional irradiation with UV/extreme UV photons to trace changes in chemical and elemental compositions of the bulk samples and specific COMs organics present (amino acids, sugar derivatives). Primary analysis techniques include IR microscopy, GC-MS, and C,N,O-XANES spectroscopy. The results will be compared with meteoritic data for soluble organics and IOM.

Significance and Relevance: This research will determine the effects of N_2 and O_2 in ices believed to be present in the cold parts of protoplanetary disks on the chemical and elemental compositions of the material that ends up being incorporated into planets, asteroids, and comets. We will explore the link between radiation processing of mixed molecular ices, radiation processing of COMs of astrophysical relevance, and extraterrestrial materials, in particular meteoritic organics. This work will advance our understanding of the origin or early evolution of the Solar System, and of the materials and processes present at the onset of Solar System formation, as solicited in the Emerging Worlds Program call.

Stephen Parman/Brown University
The differentiation of Mercury's magma ocean: integrating geodynamics and geochemistry

KEY OBJECTIVE The goal of the proposal is to estimate the chemical and physical structure of Mercury's rocky interior (mantle), just after its magma ocean solidified. The accretion of Mercury likely left the planet completely molten at its birth. After the dense, Fe-rich liquid metals segregated to the center of the planet to form the core, subsequent cooling of the planet caused the molten mantle (magma ocean) to solidify. As it did so, different crystals formed, and either sank or floated, depending on their density, to form a deep cumulate layer on top of the core, or a flotation crust on the surface. Because Mercury is extremely sulfur-rich, compared to other planets, its magma ocean also produced voluminous amounts of immiscible liquid sulfides as it solidified. The presence of these sulfide liquids would have had a major effect on how the magma ocean crystallized, by changing how the crystals and melts could separate, how radioactive (heat-producing) elements were distributed in the mantle, and by potentially forming coherent sulfide layers within the mantle or crust. Due to the sulfides, Mercury's primary chemical differentiation would have been distinct from all other terrestrial planets.

So the key to understanding what happened during Mercury's initial differentiation is to understand the sulfides: when they formed, what their compositions were and what they did to the physics of melt-crystal separation. Our proposed work would experimentally measure the composition and physical properties of all phases, including the sulfides, that formed in the magma ocean. We will then use that information in numerical models to predict the chemical and physical structure of the fully solidified magma ocean. This primary differentiation of Mercury's interior sets the starting conditions for the subsequent evolution of the planet. Many of the features observed on Mercury may be the consequence of its earliest history.

METHODS   The proposed research will use high pressure experiments at Brown to measure the composition of phases forming in the solidification of the magma ocean, including the distribution of radioactive, heat-producing U, Th and K. Thermodynamic parameters (pressure, temperature, oxygen fugacity and magma ocean composition) will be varied to explore a range of plausible magma ocean scenarios. Crystal and liquid compositions will be measured by electron microprobe and by laser-ablation inductively-coupled mass spectrometry at Brown. In addition, the surface energies of the silicate and sulfide melts will be measured by both 2D backscattered electron imaging (at Brown) and by 3D tomographic imaging (at the APS synchrotron facility in Argonne, IL). The compositional and physical data produced by the experiments will then be used in numerical models of crystals separating from a two-liquid (silicate and sulfide) magma ocean. As with the experiments, conditions in the numerical models will be varied over a range of plausible conditions.

SIGNIFICANCE   A fundamental goal of NASA and the Emerging Worlds program is to understand how planets initially differentiate. This proposal directly addresses this goal, as the main product will be a series of models that predict how Mercury's magma ocean solidified and differentiated. The results will help in the ongoing efforts to understand the observations made by the MESSENGER mission, should inform the future observations that will be made by ESA's Bepi-Columbo mission and help with envisioning and planning of future NASA missions to Mercury.

Matthew Pasek/University Of South Florida, Tampa
Phosphorus(IV) as a missing link in phosphorus cosmochemical evolution

Phosphorus (P) minerals are important to understanding the cosmochemical evolution of our solar system. From trapping volatiles in phosphates such as apatite, to indicating conditions of core-mantle differentiation, to participating in volatile chemistry as part of the organic inventory of carbonaceous chondrites, the element phosphorus provides useful information on multiple aspects of the emerging solar system. In contrast to geochemical studies of P where P is usually synonymous with "phosphate", cosmochemical studies of P acknowledge reduced oxidation state P such as metal phosphides as a substantial reservoir of the element in the solar system. As part of our prior studies of P in the solar system wherein we investigated how phosphides oxidize over time, we discovered that there may exist a stable or metastable oxidation state of P -- either +3 or +4 -- that could provide useful information on several aspects of P cosmochemistry, including how well P exchanges for Si in silicate mineral frameworks, and if there are easy routes to generating organophosphorus compounds using this metastable phosphorus compound.

We thus propose to investigate 1) the speciation of phosphorus as it oxidizes under high temperature conditions (500-1000 °C) by extracting P phases using isotopically-labelled water and analyzing these species using 31P NMR and MS techniques specifically focusing on the metastable intermediate oxidation state we observed and how it forms, 2) investigating the speciation of P in synthetic and natural phosphoran olivine via NMR and EPMA techniques, to see if phosphorus as P4+ exchanges readily for Si4+, or as P3+ and P5+ exchanges for 2Si4+, or if P is only present as phosphate, with a goal of comparing these findings to olivine in pallasites, and 3) identify if the partially-oxidized schreibersite is capable of forming phosphonic acids more readily than other P sources, focusing special attention on the free radicals generated by such chemistry and using a combination of NMR, EPR, and MS techniques in this effort.

We anticipate that the above work will be useful in understanding if there is a stable or metastable "in-between" oxidation state of phosphorus that can provide an understanding of some of the more unusual P mineralogic features that have been observed over time. Specifically, the proposed work would address whether this partially oxidized P is a "missing link" between phosphide and phosphate, that enables phosphorus to behave in ways different than these two oxidation states are otherwise capable of doing.

The proposed work is directly relevant to the goals of the Emerging Worlds program in that the proposed work investigates the chemistry of phosphorus in the materials present when the solar system was forming, and the evolution of phosphorus as the first solids began to evolve (especially as part of differentiation and accretion, e.g., section 2.2. of the C.2 Emerging Worlds research announcement). The proposed work will identify both how specific minerals in meteorites originated, how some meteorite organics may have originated, and how phosphorus -- under the specific set of conditions present under the low redox conditions of the solar system -- evolved to generate several key minerals. This work is also hence relevant to NASA's SMD goal of understanding "How did the solar system evolve to its current diverse state?" Additionally, as phosphorus is a critical element for biology, it may also be relevant to understanding "What are the characteristics of the Solar System that lead to the origins of life?", as the phosphonic acids have often been used as proxies for a meteoritic role in the development of life on the earth.

Alan Rubin/University of California, Los Angeles
Compositions and Parent-Body Processes in Chondrites and Irons

This is a request for a small three-year grant to allow Alan Rubin (P.I.) to travel to scientific meetings and conduct the following five research projects in collaboration with Bidong Zhang (UCLA) and Nancy Chabot (Johns Hopkins). The proposed projects include: (1) Determining and accounting for a newly discovered major reduction feature affecting many L-group chondrites that may be related to the shock event that disrupted that parent body. (2) Sifting through about 100 unpublished INAA data for carbonaceous chondrites (from all major CC groups) obtained by John Wasson that will significantly augment the numbers of such analyses in the literature. (3) Modeling the fractional crystallization and impact history of IVA irons. (4) Modeling the impact history of four ungrouped CC irons (the closely related members of the Nordheim Trio as well as Chinga). [The Nordheim Trio includes Nordheim, ALH 77255 and Babb's Mill (Blake's Iron).] (5) Modeling the fractional crystallization histories of all CC-iron groups (IIC, IID, IIF, IIIF, IVB) as well as the South Byron Trio (South Byron, Babb's Mill (Troost's Iron), ILD 83500). This work is highly relevant to the scope of the Emerging Worlds program and will provide important constraints on parent-body processes during the early epochs of Solar-System history.

Solar System Workings
Abstracts of Selected Proposals
(NNH21ZDA001N-SSW)

Below are the abstracts of proposals selected for funding for the SSW program. Principal Investigator (PI) name, institution, and proposal title are also included. 81 proposals were received in response to this opportunity. As of February 15, 2023, 28 proposals have been selected for funding.

Jeffrey Andrews-Hanna/University Of Arizona
Mars during the Pre-Noachian

The pre-Noachian epoch on Mars the time period bounded by the formation of the crustal dichotomy and the Hellas basin is the least understood period of martian history. While the geological record was reset by impacts at the start of the early Noachian, a geophysical record of the pre-Noachian persists. This record is most clearly manifest in the crustal dichotomy boundary, which remains as a distinct step in topography and crustal thickness despite its great antiquity. The preservation of this feature places a strong constraint on the conditions during the pre-Noachian. The proposed work will constrain the allowable ranges of processes and associated structures on pre-Noachian Mars that can be reconciled with the geophysical record. The first task will focus on the timing of the major basin-forming impacts on Mars and the duration of the pre-Noachian using Monte Carlo models of impactor populations compared with constraints on the timing of the major basin forming impacts. Preliminary results of this task indicate that one of two scenarios is correct: either the existing chronology of Mars is correct and Mars experienced a late heavy bombardment from a distinct population of impactors, or Mars experienced a single declining bombardment and the accepted chronology of basin-forming impacts and the duration of the Noachian are dramatically incorrect. Either possibility has significant implications for the history of pre-Noachian and Noachian Mars. The second task will explore the nature of pre-Noachian Mars, using the preservation of the dichotomy boundary as a key constraint. We will model the pre-Noachian modification of the dichotomy boundary by viscous relaxation, impact cratering, and fluvial erosion. Results of this task will have significance for our understanding of the thermal evolution of the crust, as well as the bombardment history and climate of the pre-Noachian. The third task will build upon the previous task to explore the range of possible surface features that could have formed during the pre-Noachian and been lost from the geologic record. Using our new constraints on the bombardment and erosion history of the pre-Noachian, we will model the modification of a range of possible analog structures (e.g., volcanoes and rifts). Results of this task will provide significant constraints on the range of processes that could have operated and structures that could have formed during the pre-Noachian. Collectively, these three tasks will shed light on the geological and geophysical processes operating during the pre-Noachian period of Mars the time period which we know the least about, but also the time period in which Mars is expected to have been most geophysically active and perhaps to have had the warmest climate and thickest atmosphere.

Janice Bishop/SETI Institute
Characterization of Low-Hydrate Mg and Fe Sulfates to Support their Detection on Mars

Unusual types of sulfates have been identified at several locations on Mars by a spectral band near 2.23 µm in orbital CRISM spectra that is not explained by known minerals. Lab experiments have shown that these unusual martian outcrops may be low-hydrate Fe sulfates that contain all or mostly OH instead of H2O in the mineral structure. Fe hydroxy sulfates, Fe(SO4)OH and magnesium hydroxide sulfate hydrates (MHSH), MgOH(SO4)H2O, are examples of low-hydrate sulfates. They are uncommon or unknown on Earth outside of the lab but would be stable in the current dry martian environment. We propose a coordinated effort to characterize low-hydrate sulfates in the lab to enable their detection on Mars.

Sulfates on Mars represent a large component of the hydrous materials on that planet, including polyhydrated, monohydrated, and hydroxylated minerals with Fe, Mg, and Ca cations. Many of the monohydrated sulfates are not consistent with either kieserite (100% Mg) or szomolnokite (100% Fe) and could contain a mixture of these cations. We have designed a project to produce a variety of low-hydrate Mg, Fe2+, and Fe3+ sulfates under multiple conditions. We propose to characterize the spectral properties of these low-hydrate sulfates, using observations of Mars to guide our experiments. This study will produce XRD data, VNIR, mid-IR, and Raman spectra at room temperature and lower temperatures down to -90 °C to probe the structure of these samples (including OH and H2O) and evaluate changes in the spectral and XRD parameters under Mars-like temperatures. The objectives of this study are to understand the nature of water and OH in sulfates on Mars, to characterize the formation, stability, and spectral properties of Mg, Fe2+, and Fe3+ low-hydrate sulfates, to constrain the environmental conditions on Mars supporting sulfate formation and stability, and to provide tools for detecting these sulfates on Mars.

Three groups of sulfates including monohydrated and polyhydrated sulfates with variable Mg, Fe2+, and Fe3+ cations are available for our project. We propose to perform dehydration experiments on these samples to produce low-hydrate sulfates. This will include i) heating the samples under different temperatures (100-300 °C) and measuring XRD and VNIR spectra at intervals to assess structural changes during the experiments, ii) measuring TGA and high-temp mid-IR spectra to monitor changes with dehydration, and performing low-temp NIR/Mid-IR and Raman experiments, and iii) synthesizing the spectral, XRD, and chemical data to understand the spectral properties and formation conditions of low-hydrate sulfates and pulling this data together to improve options for identifying and characterizing sulfates on Mars.

Unusual outcrops of hydroxy sulfates have been identified at Aram Chaos, Capri Chasma, and Juventae Chasma with a narrow band near 2.3 µm (at either 2.226 or 2.238 µm). We suspect that spectral differences are due to Mg substitution for some Fe or the ratio of OH/H2O in the sample and the proposed experiments will define the position of this band for different sample chemistries and structures. Another unusual material is observed at Ius Chasma, Noctis Labyrinthus, and Mawrth Vallis with two bands near 2.23 and 2.27 µm. This spectral doublet" outcrop could be related to the sites containing the 2.23 µm band because the sulfate jarosite containing OH groups has a band at 2.27 µm and could be occurring together with the Fe(SO4)OH phases proposed here. Further, jarosite is present at Juventae Chasma, supporting its association with the low hydrate sulfate observed here. Gale crater contains a variety of sulfates, including some sulfate phases that are not yet understood. This study will provide new lab data on low hydrate sulfates to assist their identification using VNIR data from orbit and XRD, mid-IR and Raman spectra on rovers.

Benjamin Cardenas/Pennsylvania State University
Can martian fluvial ridges be used to measure structural tilt?

On Mars, fluvial ridges are sinuous, high-standing erosional landforms that are thought to have formed from the exhumation and inversion of river-channel deposits. It has been hypothesized that along-ridgetop topographic profiles should be flat unless structurally tilted. However, a counter hypothesis has also been argued, that differential erosion may be the more important process that defines ridge-top topography, obscuring structural tilt. The objective of the proposed work is to test these hypotheses against each other and answer the question: can structural deformation on Mars be measured using the along-ridgetop slopes of fluvial ridges?

To achieve the proposal objective, I have already acquired a freely available 3D seismic volume of analog Earth stratigraphy 100s of m thick and 10s of km across that images over 50 untilted river-channel deposits. The volume is processed to show rock type, with channel deposits being sandstone and adjacent floodplain deposits being mudstone. I will use this stratigraphic volume to complete three Tasks: (1) numerically tilting this stratigraphy to 41 different orientations, (2) using a numerical erosion model to erode these tilted stratigraphic volumes at different rates based on rock type, creating 41 synthetic landscapes with fluvial ridges, and (3) measuring synthetic ridge-top slopes to see if their orientations match the imposed tilt. Preliminary results have successfully tested Tasks 1 and 2.

In short, there is interest in measuring deformation at Mars' surface. If our results show fluvial ridges are useful in measuring deformation, that is significant because fluvial ridges exist at many locations across Mars. Reconstructing the tilting of martian crust is important for understanding the elevation spread of ancient shorelines, crustal loading from volcanism or a northern ocean or ice sheet, the effects of large impacts, Mars' crustal thermal history, groundwater and soft-sediment deformation, reconstructions of paleo-stratigraphic dips, river paleoflow directions, and subsurface ice. Consistent with the SSW program scope, the results from this research will fill a fundamental void in our basic understanding of physical processes affecting planetary surfaces and interiors, with significant implications for unraveling the history of landscape evolution, surface water, and crustal deformation on Mars. With the work being based on comparative planetology and modeling, the proposal is suited for the SSW program and not for the MDAP program. It seeks to answer a process-based question rather than a specific regional understanding, aligned with SSW objectives. In addition, the proposed research is relevant to research objectives identified by the Mars Exploration Program Analysis Group Goal III: document the geologic record preserved in the crust and investigate the processes that have created and modified that record, which is considered higher priority.

Matija Cuk/SETI Institute
Orbital Evolution of Saturn's Moons by Resonance Locking

The age and orbital history of Saturn's major moons are actively debated topics, as are the potentially related questions of the origin and age of Saturnian rings. The idea that primordial moons experienced a multi-Gyr orbital evolution, driven by equilibrium tides, has been all but abandoned. Two alternative explanations of the history of the system have recently been proposed. One hypothesis suggests that the moons evolve much more rapidly than previously believed (Lainey et al. 2012), implying that the present system of the moons interior to Titan is only about 100 Myr old, and suggests that the rings and inner moons originated in a cataclysm (Cuk et al. 2016). The other view advocates for an orbital evolution driven by resonance locking with structures within Saturn (Fuller et al. 2016), and is supported by recent astrometric measurements for Rhea and Titan (Lainey et al. 2017, 2020). In this latter hypothesis, the inner moons do not usually encounter mutual orbital resonances, and both moons and rings can be billions of years old. Although we have developed models of the moons' orbital history resulting from equilibrium tides, the full implications of resonance locking have yet to be explored. Here we propose to investigate three questions pertaining to the evolution of the Saturnian system under resonance locking.

In Task 1 we will explore the past passage of Rhea through the evection resonance with the Sun. Our preliminary simulations of this crossing suggest a significant excitation of Rhea's eccentricity and inclination. In our preliminary results, Rhea's final orbital inclination is well in excess of the observed value. While a moon's eccentricity may be damped through tides, tidal damping cannot, by itself, resolve this discrepancy. We propose to test different parameters of resonance locking tides to determine if this excitation of inclination is inherent to the system, or a parameter-dependent effect. The resolution of this question is important: if Rhea's present orbit cannot be reconciled with passage through the evection resonance, Rhea (and potentially other moons and rings) must be relatively young, even if resonance locking is evolving the Saturnian system.

In Task 2 we propose to study the evolution of the Titan-Hyperion 4:3 mean-motion resonance (MMR) under resonance lock. Recent measurements of the evolution of Titan strongly support resonance locking (Lainey et al. 2020). However, this evolution orbital rate requires a sub-Gyr age for the resonance with Hyperion. As Hyperion is too small and remote to enter a resonance lock, prior to entering the mean-motion resonance, it would not have been protected from encounters with Titan. This would require Hyperion to be much younger than the age of the Solar System, challenging the primordial moon paradigm. We propose to numerically model the Titan-Hyperion 4:3 MMR resonance at realistic evolution speeds, and more reliably constrain the age of Hyperion.

In Task 3 we will explore the equilibrium tidal heating of Enceladus, driven by a simultaneous resonance lock with Saturn's inertial waves and its MMR with Dione. Analytical calculations suggest that two inertial waves with a sidereal period ratio just within the 2:1 commensurability and with precisely equal evolution timescales are necessary to maintain Enceladus and Dione in equilibrium. Using direct numerical simulations, we propose to test whether this dynamical state is viable and stable.

The results of our Tasks 1 and 2 will constrain the ages of individual moons, while Task 3 will test the applicability of resonance locking to Enceladus.

Our proposal aims to explore how the Saturnian system evolved over time, and to constrain the energy source and age of the potentially habitable environment on Enceladus, which aligns this proposal with NASA's strategic objective to advance scientific knowledge of the origin and history of the solar system and the potential for life elsewhere.

Chuanfei Dong/Boston University
Modeling Martian Atmospheric Losses over Time

Science goals and objectives: Mars is a vital target from the standpoint of planetary science, especially on account of its past, perhaps even its current, astrobiological potential. Ancient Mars (~ 4 Ga) has garnered significant attention because it potentially had aqueous environments with water-rock interactions, minerals, bioessential elements, energy sources for prebiotic chemistry, and possibly oceans; these factors could have collectively enhanced the prospects for its habitability. One of the most striking differences between ancient and current Mars is that the former possessed a much thicker atmosphere compared to present-day Mars, thereby making it presumably more conducive to hosting life. This discrepancy immediately raises the question of how and when the majority of the Martian atmosphere was depleted as well as the channels through which this occurred. The primary objective of the proposed work is to investigate the atmospheric loss and evolution of Mars via its interactions with solar wind and radiation (including extreme space weather events) over time.

Methodology: The most sophisticated codes draw upon magnetohydrodynamic (MHD) models for modeling solar wind interactions with terrestrial planets such as Mars. We will deploy a one-way coupled framework (namely, the 3D Mars ground-to-exobase whole atmosphere, 3D Mars exosphere, and 3D solar wind models) centered around a thoroughly-validated 3D Mars multifluid magnetohydrodynamic (MF-MHD) model to study Martian atmospheric escape and evolution over time. In the one-way coupled framework, MF-MHD adopts the neutral thermospheric profiles from the ground-to-exobase Laboratoire de Météorologie Dynamique-Global Climate Model (LMD-GCM) and the exospheric profiles from the Mars exosphere Monte Carlo model - Adaptive Mesh Particle Simulator (AMPS); the latter can also be applied to study Martian photochemical escape. For solar wind parameters (e.g., solar wind velocity, density, temperature, and interplanetary magnetic field) of different epochs, especially during the epoch of the young Sun, we will adopt the Alfven Wave Solar Model (AWSoM) to simulate those parameters self-consistently (including extreme space weather events such as CMEs - coronal mass ejections, CIRs - corotating interaction regions, super Carrington-type flare events) based on stellar observations (e.g., magnetograms/ZDI maps and flares) of solar-type stars of different ages.

Relevance: The proposal is highly relevant to the ROSES Solar System Workings (SSW) program since the proposed research ranges from planetary atmospheres to their magnetospheres. All of these elements, which are encapsulated by our work, constitute the central targets and primary objectives of the SSW program. In addition, the proposal is highly relevant to NASA's Planetary Science Division's current (e.g., MAVEN, MSL, and Mars 2020) and future missions to Mars (e.g., EscaPADE) for studying Martian atmospheric loss, long-term climate evolution, and habitability.

Colin Dundas/USGS Flagstaff
Understanding scenarios for ice emplacement in Athabasca Valles, Mars

Rootless cones form when lava flows over wet ground, causing steam explosions. Rootless cones in Athabasca Valles on Mars show that water was present in the shallow subsurface at the time of a recent lava eruption. This water is expected to have been in the form of ice, but Athabasca Valles is near the equator, where ice would rapidly sublimate in the current climate. The source of the ice is a puzzle; the leading hypotheses are that it was deposited (i) from the atmosphere in a different climate, or (ii) by a megaflood shortly before the lava was erupted. The answer will place important new constraints on one of two major problems in Mars science:

- If the ice was deposited from the atmosphere, that will place a strong constraint on the climate several million years ago; this is needed because published models give divergent results on whether ice was stable in this region over this time period.
- If the ice was deposited from a recent megaflood, that demonstrates the survival of aquifers within the last <1% of Mars's history, showing that habitable environments remain at depth, and that outflow channel floods have continued in geologically recent time.

This project will investigate the origin of the ice via two independent, but complementary, modeling efforts. The first will determine the fluxes and volumes required of an aqueous flood that would carry water 1400 km to the most distal rootless cones associated with Athabasca Valles. It appears quite possible that these values will be incompatible with plausible parameters for a Mars aquifer, which would argue against a diluvial origin for the ice. Alternatively, this effort could place important new constraints on the nature of the extant habitable environment deep within Mars. The second modeling effort will determine what climatic conditions result in ice not only being stable, but actually accumulating, in the equatorial regions of Mars. If the diluvial model is shown to be unlikely, these results will indicate the climatic conditions at the time of the Athabasca Valles eruption. If both atmospheric and diluvial ice remain viable after this study, we will have delineated both hypotheses sufficiently to allow new tests to be developed for each.

This project will carry out modeling of flood processes and atmospheric ice deposition on Mars, and thus fulfils the Solar System Workings objective to support research into atmospheric, climatological, dynamical, geologic, geophysical, and geochemical processes occurring on planetary bodies&in the Solar System". It investigates fundamental atmospheric, climate, geological and geophysical processes on Mars.

Tony Farnham/University of Maryland, College Park
Deep Imaging with TESS: Studying Distant Comets, Dust Trails and Other Faint Phenomena.

We propose to perform a study of ~140 comets that serendipitously appear in Cycles 1-4 (Sectors 1-47) of NASA's Transiting Exoplanet Survey Satellite (TESS) observations to study their faint features and evaluate important characteristics of these objects. The satellite's instrumental stability and continuous, high cadence sampling during each 27-day sector allows thousands of frames to be coadded to produce deep images, revealing faint phenomena not detectable by other means. Among our goals will be: to search for dust trails, observable along cometary orbits out to large distances from their parent nuclei, which we will use to derive properties of the large grain populations and production rates for dozens of objects; and to hunt for comae in distant objects, which will set constraints on physical and compositional properties of the nuclei. The large number of comets in the TESS data will provide statistically significant samples of these phenomena, enabling meaningful comparative comet analyses. We will explore correlations with other cometary properties to look for the broader implications of these structures and will use the aggregate results from the trail studies to set constraints on cometary contributions of outer Solar System dust and organics to the inner Solar System.

Given the volume of data and number of comets in the survey, automation is critical for an efficient study. We will use TESS user-provided software as well as developing our own routines for removal of scattered light and background stars, and for producing coadded images that preserve the image photometry. We will use existing dust dynamic routines to derive dust properties and cometary production rates.

Due to the number of dust trails detected in the TESS data, and the suitability of the data for use in deriving dust properties, this study has the potential to revolutionize dust trail studies. It will also provide a meaningful estimate of the amount of organics-rich dust that is transported from the outer to the the inner solar system by comets. All aspects of this study are relevant to the stated goals of the SSW program. Our study is not relevant to other NASA programs, as we will obtain no new data, and solar system studies are not included in the Astrophysical Data Analysis Program (ADAP) that typically funds TESS research.

Sarah Greenstreet/University of Washington, Seattle
Searching for Transient Jovian Co-orbitals

A population of over 9,000 long-term stable objects co-orbit the Sun with Jupiter near either the L4 (leading) or L5 (trailing) Lagrange points, 60 deg ahead of or behind Jupiter, respectively, and are defined to have orbits that are stable on primordial (>4 Gyr) timescales. However, the population of known Jupiter Trojans are not identified as such by the Minor Planet Center (MPC) through rigorous resonant analysis. As a result, mis-classifications of Jupiter Trojans are coming to light, such as for (514107) Ka'epaoka'awela 2015 BZ509 and 2019 LD2. It is expected that as many as 100 asteroids and Centaurs with diameters d>1 km are captured as jovian co-orbitals on temporary (<a few Myr duration) timescales. Only one (2015 BZ509) has been identified to date, which the MPC classifies as on a main-belt orbit and not a Trojan (or more correctly as a transient jovian co-orbital). In addition, 2019 LD2 was recently found to have cometary activity and has been identified as an active Centaur transitioning to the inner Solar System, despite its MPC classification as a primordial Jupiter Trojan. Due to the lack of accurate identification of objects not long-term stable in and near the Jupiter Trojans through rigorous resonant analysis, we will study this sample. The goals of this proposed project are to (1) securely identify the primordial Trojans, transient co-orbitals, and transitionary objects among the population in and near the Jupiter Trojans; (2) produce an automated pipeline to classify the resonant behavior of objects in the near-Jupiter region detected in current survey alert streams; and (3) scale-up our automated pipeline to classify objects in and near the Trojans found among the alert stream detections of upcoming surveys such as the LSST early observations (expected to be available in late 2023).

We will use numerical integrations of observationally-derived orbits and large numbers of clones within the orbital uncertainty region to search for semimajor axis oscillation around Jupiter's semimajor axis as well as resonant argument libration for periods of time long enough (>5 kyr) to distinguish transient co-orbital capture or transitionary behavior from primordial Trojan stability. The algorithm will be similar to our previously developed co-orbital detection algorithms. The algorithm will then be adapted and automated to analyse detections and discoveries made by current surveys such as Pan-STARRS, ZTF, and ATLAS and upcoming surveys such as LSST (expected to start in late 2023) in roughly real-time.

A significant outcome of the resonant classification database will be the identification of transitionary objects and recently captured transient co-orbitals in the near-Jupiter population with the potential to become active bodies in the near future. As Centaurs migrate through the near-Jupiter region for the first time they will be exposed to warmer temperatures, which can induce cometary activity as their pristine surfaces respond to the changing thermal environment. Dynamical studies of 2019 LD2 show it is likely a Centaur recently arrived near Jupiter for the first time on its path to the inner Solar System, which likely explains its recent cometary activity. The identification of hundreds of transient co-orbitals and transitionary objects in and near the Trojan population could provide the rare opportunity for NASA's forthcoming Lucy mission to characterize objects undergoing current or recent activity as they pass through the near-Jupiter region by spacecraft for the first time. This would improve our understanding of the effects of a changing thermal environment on these pristine objects.

In addition, we will compute libration amplitude distributions of all primordial Trojans and transient co-orbitals identified to be librating. These libration amplitudes can then be compared with models of early Solar System evolution such as the Grand Tack model of Jupiter's migration through the inner Solar System.

Steven Jaret/Kingsborough Community College
Shock Recovery Experiments and Laboratory Sample Analysis of Lunar-Relevant Plagioclase: Implications for remote observations of the Moon

Alteration of the surfaces of the Moon and other airless bodies due to interactions with the space environment is broadly known as space weathering and encompasses effects from both irradiation by the solar wind and micrometeorite impacts. However, shock and other effects from large impacts can also alter surface material, and specific contributions of either impact or irradiation are not well established nor quantified. In order to disentangle effects of impact from irradiation induced damage, we propose a series of shock experiments on lunar-like anorthite followed by infrared reflectance spectroscopy and transmission electron microscopy of shock recovery experiments.

Specifically, we have the following objectives:
A) Characterize the shock effects in plagioclase of lunar composition in the near infrared (NIR) and mid infrared (MIR) spectral range
B) Determine the mechanism of deformation and alteration through coordinated petrographic, spectroscopic, and transmission electron microscopy (TEM) analyses
C) Determine the effect of particle size and porosity on the production of and remote detection of shock effects in lunar-relevant plagioclase through comparison of experimentally shocked rocks and a fine particulate regolith analog

To accomplish these goals we will conduct the following tasks
Task 1: Shock recovery experiments at the Johnson Space Center Flat Plate Accelerator (FPA) and petrographic analysis of recovered
materials at the American Museum of Natural History
Task 2: NIR and MIR spectroscopy of pre- and post-shocked material at University of Oxford
Task 3: Transmission Electron Microscopy at the Naval Research Lab

The proposed work is relevant to the Solar Systems Workings program, "which supports research into atmospheric, climatological, dynamical, geologic, geophysical and geochemical processes occurring on planetary bodies." Impact cratering and shock metamorphism are dominant geologic processes that we are investigating with application to the Moon. The results from our investigation will also enable better interpretations of observations of Mercury and other airless bodies with crusts that include feldspar-rich materials. This work also falls within the subcategory of "evolution and modification of surfaces" (C-3 of the Solar System Workings solicitation), which specifically denotes impact craters and related processes.

Ralf Kaiser/University of Hawaii, Honolulu
Exploring the Photochemical Processing of Ethane Droplets in Titan's Atmosphere in a Novel Ultrasonic Levitation Setup

Key Objective/Significance: The objectives of this pilot study are two-fold. First, it is our goal to commission an ultrasonic levitation device capable of preparing, levitating, and spectroscopically characterizing low-temperature super-cooled ethane (C2H6) droplets doped with hydrocarbons [methane (CH4), acetylene (C2H2)] and nitriles [hydrogen cyanide (HCN)] as the dominant hydrocarbons and nitriles in a Titan-analog atmosphere. Second, we unravel the photochemically-induced formation of complex organic molecules in these droplets by exposing droplets to ultraviolet (UV) photons (200 400 nm), which are capable of reaching Titan's troposphere, i.e. the region where super-cooled ethane droplets are present, in laboratory simulation experiments. This is achieved by characterizing the chemical and physical changes of these droplets spectroscopically via infrared (IR), Raman (Ra), and ultraviolet-visible (UV-VIS) spectroscopy during the photochemical processing. These studies are of fundamental significance to the planetary science and Titan community in particular. First, the unraveling of the photochemical processing of super-cooled ethane droplets via low energy ultraviolet radiation reveals novel information on the chemical evolution and transport of chemicals throughout the atmosphere of Titan. Second, results from the low energy photolysis of simulated Titan hydrocarbon rain droplets will aid in understanding the surface composition of Titan. Third, an understanding of Titan's droplet chemistry and the potential formation of aromatic molecules is of tremendous importance from the astrobiological viewpoint.

Methodology/Approach: This project develops novel technology capable of levitating low temperature, super-cooled ethane-based droplets under Titan's atmospheric conditions and of providing new knowledge on the organic molecules formed in these photochemical processes. Therefore, in this pilot study, we first develop new technology in form of an ultrasonic levitation device capable of levitating doped hydrocarbon droplets in concert with spectroscopic techniques that have not been previously available via a rigorous in situ near/middle infrared (FTIR), Raman (Ra), and ultraviolet-visible (UV-VIS) spectroscopy of the photolyzed droplets. Second, we aim to demonstrate as a proof-of-concept, that this approach enables the identification of key functional groups of newly formed molecules in low temperature liquid droplets upon photolysis under characteristic chemical and physical conditions exploiting a nitrogen-based Titan analog atmosphere.

NASA Relevance: Results from this proposal directly overlap with the goals of NASA's Solar System Workings program to investigate 'atmospheric processes occurring on planetary bodies, satellites in the Solar System.' This proposal also addresses the call for the exploration of 'chemical processes that effect the surfaces and atmospheres of planetary bodies' (here: Titan). This program is open to investigations relevant to atmospheres (here: droplets in Titan's troposphere) to 'solve key questions' (here: the chemistry of droplets) covering 'the physical and chemical processes' (here: photolysis, droplets) 'affecting planetary systems' through 'laboratory studies'. The photochemistry of droplets represents 'fundamental processes at work' which eventually change the chemical composition of Titan's surface as well. More specifically, our project untangles the evolution of droplets in the atmosphere of Titan, which ultimately deposit as 'rain' on Titan's surface, through an understanding of the underlying fundamental chemical and physical processes in liquid droplets of super-cooled ethane. This project presents an exceptionally well-timed interdisciplinary opportunity to deliver fundamental knowledge, which is of key relevance for the future Dragonfly mission to Titan.

Laura Kerber/Jet Propulsion Laboratory
Understanding Pyroclastic Cones Through Imaging Spectroscopy

Maar-diatreme volcanoes have been proposed as desirable rover targets on Mars, and may soon be visited by the Tianwen-1 mission. The goal of this project is to understand maar-derived pyroclastic cones by rapidly mapping the compositional distribution of country rock fragments over a wide area in a terrestrial maar volcano in Mexico, using a state-of-the-art imaging spectrometer in the field. This data set will be used to evaluate the leading hypothesis for maar volcano evolution and to determine how spectral information from pyroclastic cones may be used to investigate the nature of subsurface layers on Mars.

In this project, we propose to use a field-portable imaging spectrometer system to image pyroclastic surge exposures in different areas with increasing distance from the vent. The imaging spectrometer system was previously used to create a map of the composition of impact melt-bearing breccias within Haughton impact crater in the Canadian Arctic to compare with known substrate stratigraphy (Greenberger et al., 2020). Following this approach, we will examine a maar with well-known country rock stratigraphy (Crater Elegante, northern Mexico) so that the process by which a tuff cone excavates and exposes country rock can be elucidated. To validate the approach, samples from each exposure will be collected and examined in the laboratory using traditional techniques to identify the compositions of their lithic clasts. This investigation will provide a basis for understanding the fragmentation and emplacement of lithic clasts that could be put to immediate use by the Tianwen-1 rover team and any future mission that visits a pyroclastic cone.

Relevance to SSW: This investigation addresses how “volcanic activity can provide insight into interior processes” and how “volcanic activity can modify planetary surfaces”. As a field-based study, it does not fall under the purview of the data analysis programs.

Frieder Klein/Woods Hole Oceanographic Institution
Aqueous Alteration of a CI Chondrite Simulant Relevant to Enceladus and Other Primitive Solar System Objects: Constraints from Laboratory Experiments

The alteration of ultramafic rocks including carbonaceous chondrites by aqueous fluids is recognized to have been widespread across the solar system since its formation, with important implications for the chemical and physical evolution of planetary bodies and their habitability. Theoretical models and studies of carbonaceous chondrites have provided important insights into possible alteration processes on meteorite parent bodies and small icy moons; however, there have been no comprehensive experimental laboratory studies examining the hydrothermal alteration of carbonaceous chondrites that focused on reaction pathways and rates of alteration while also monitoring the composition of coexisting fluids. Understanding parameters that regulate chemical interactions between water and carbonaceous chondrites is key to constrain better the environmental conditions on small, (once) water-bearing solar system objects such as meteorite parent-bodies and Enceladus, which may be undergoing hydrothermal alteration today.

The overarching objective of the proposed investigation is to develop a mechanistic understanding of reaction pathways, reaction rates, and redox conditions during aqueous alteration of primitive carbonaceous chondrite parent bodies and small icy moons by CO2-poor and CO2-rich hydrothermal fluids over a range of temperatures and pressures.

To place more robust constraints on the aqueous alteration of carbonaceous chondrites, an anhydrous Ivuna type (CI) chondrite simulant containing organic matter will be synthesized and used as an initial reactant for hydrothermal laboratory experiments. A series of hydrothermal laboratory experiments will be conducted in flexible gold cell reactors by heating the CI chondrite simulant in the presence of CO2-poor and CO2-enriched aqueous solutions at elevated temperatures (150 to 300°C) and pressures (7.4 to 30 MPa) for up to 9 months. Reacted fluids will be extracted periodically during each experiment and analyzed to determine pH, dissolved H2, CH4, and major and trace element concentrations. Reacted solids will be analyzed to determine their mineralogy, mineral composition, and extent of reaction using scanning electron microscopy, electron microprobe analysis, confocal Raman spectroscopy, and thermogravimetric analysis. Thermodynamic modeling tools will be used to trace reaction pathways and identify the governing phase equilibria (stable or metastable). The results will be evaluated in the context of mineral assemblages present in naturally occurring carbonaceous chondrites that record past alteration conditions on their meteorite parent bodies.

Yan Liang/Brown University
Thermal and Magmatic History of Martian Meteorites and Melting Processes in the Martian Mantle

The distribution of trace elements between major rock-forming minerals and basaltic melt is important in deciphering the processes of mantle melting, magmatic differentiation, and subsolidus re-equilibration. Recent advances in in situ trace element analysis make it possible to measure REE and other incompatible trace elements in minerals from martian meteorites with greater accuracy and efficiency such concentrations of a large number of geochemically important trace elements have been routinely measured and reported for martian meteorites in the literature. To interpret the trace element abundance and distribution in the meteorite samples, one has to know mineral-melt partition coefficients which vary as a function of temperature, pressure, mineral and melt compositions. It is well known that pyroxenes from SNC meteorites are low in $Al2O3$ compared to those from Earth or the Moon. Partition coefficients of many trace elements, such as REE and HFSE, for the terrestrial and lunar systems cannot be directly used to model martian samples without corrections for the composition effect. To date, there are only two studies that reported partition coefficients for selected REE in pyroxene and olivine in martian relevant compositions. One of the chief objectives of this proposed study is to provide a complete set of trace element partition coefficients and partitioning models for martian-specific major element compositions. Such martian-specific partitioning models are crucial to the interpretation of trace element and radiogenic isotope data in martian meteorites and future samples returned from Mars.

Laboratory crystal growth experiments will be conducted in systems of low-Ca pyroxene-basalt, high-Ca pyroxene-basalt, plagioclase-basalt, olivine-basalt, and garnet-basalt over a range of temperatures (1050~1500°C), pressures (0~3 GPa), and melt compositions that are relevant to SNC meteorites and martian mantle. Starting compositions will be spiked with 30 or so geochemically important trace elements. Major and trace element concentrations in quenched run products will be analyzed using an electron microprobe and a laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) at Brown University. Together with selected high-quality mineral-melt trace element partitioning data from the terrestrial and lunar literature, we will develop internally consistent lattice strain models for the partitioning of isovalent trace elements in the aforementioned mineral-melt systems using nonlinear least squares methods. As part of planetary applications, we plan to measure REE and other trace element abundances in pyroxene, plagioclase, and olivine in selected martian meteorites using the LA-ICP-MS and electron microprobe. With laboratory calibrated and martian-specific mineral-melting partitioning models, we will be able to deduce the thermal and magmatic history experienced by the selected meteorites and to study the melting processes in the martian mantle with greater confidence.

Ajay Limaye/University of Virginia, Charlottesville
Distinguishing Titan's fluvial features by comparison to terrestrial and Martian analogues

In exploring Saturn's moon Titan, the Cassini mission revealed a surface with striking resemblances to Earth. Familiar fluvial features occur at a range of scales, from rounded cobbles to drainage networks that can span hundreds of kilometers and empty into seas. These features evoke an active hydrologic cycle and suggests that Titan's landscapes are readily interpreted by adapting established theory for hydrology and sediment transport to account for the alien environment. Yet knowledge of planetary-scale fluvial processes on Titan comes largely from radar images limited to resolutions of 250 m at best, and more commonly ~1 km. This limited resolution could confound interpretation of fluvial landforms, which are often nested at multiple scales. For example, a river channel usually sits within a larger-scale feature such as a river valley or sedimentary plain (i.e., channel belt). Channels, valleys, and channel belts can all create networked features. Therefore, current data for Titan's surface leave a fundamental ambiguity: are widespread, sinuous features in radar images channels, or instead the larger valleys or channel belts that they inhabit? The main objective of this proposal is to resolve ambiguity in the nature of fluvial features on Titan through comparative analysis of well-resolved feature analogues on Earth and Mars. Our research team will combine expertise in fluvial processes (PI Limaye, U. Virginia) and Titan's surface (co-I Hayes, Cornell U.) to test this hypothesis as follows. In Task 1, we will use existing data and new analyses to develop a large-scale, a database of known fluvial features (Earth and Mars) and ambiguous features on Titan. In Task 2, we will test for geometric criteria that distinguish the known fluvial feature types (channels vs. valleys vs. channel belts). We will then apply these criteria to interpret ambiguous, sinuous features on Titan. In Task 3, we will reassess fluid discharge estimates for Titan channels. We anticipate that these analyses will advance Titan science by clarifying the scale of channels, thereby providing new constraints for landscape evolution and surface/near-surface hydrocarbon transport. This work will further enhance potential science return from NASA's Dragonfly mission to Titan in the mid-2030s by developing testable hypotheses that will support target prioritization, developing a high-resolution dataset of terrestrial features support future interpretations for Titan, and enabling translation of Dragonfly's in situ findings to unexplored regions.

Mark Loeffler/Northern Arizona University
Determining the Role of Space Weathering on Hydrated Asteroids through Laboratory Studies

It is well-known that solar wind particles and micrometeorite impacts alter the surface regolith of airless bodies, such as the Moon and asteroids, and these processes are typically referred to as space weathering. On the scale of the regolith grains, these alterations are manifested through physical and chemical changes of the outer layers, which can be due to a combination of direct irradiation or redeposition of material evaporated during irradiation. Historically, laboratory studies have primarily focused on the effects that these processes have on the spectral reflectance in the visible-near-infrared region. However, using this spectral region to gain insight into the composition and potential alteration of carbonaceous asteroids' surfaces has proved challenging, because these objects typically are dark and lack in diagnostic features in the near-infrared region. As recent measurements suggest that many of these asteroid surfaces contain hydrated minerals, it appears that the spectral region near 3-µm could prove critical for characterizing the surface of many carbonaceous asteroids. While there have been a number of laboratory efforts to characterize the 3-µm spectral region of carbonaceous chondrite meteorites, the presumed parent body of carbonaceous asteroids, laboratory studies investigating how and to what degree this spectral region can be altered by space weathering are generally lacking.

We propose to investigate space weathering in carbonaceous chondrite meteorites focusing on how the 3-µm spectral region, as well as the structural and chemical properties of these samples are altered by ion and laser irradiation. In this three-year study, we will build on our experience studying space weathering of chondritic lunar and asteroid analogs by examining weathering in relevant carbonaceous chondrite meteorites induced by laser and ion irradiation. This study will be the first to systematically investigate both space weathering processes in a suite of relevant meteorite samples, using regolith-like samples, as well as the first to study the three main processes (direct laser irradiation, direct ion irradiation, and vapor redeposition) using the same experimental setup.

Using mid-infrared reflectance spectroscopy (mid-IR), X-ray photoelectron spectroscopy (XPS), and transmission electron microscopy/energy dispersive spectroscopy (TEM/EDS) as our main diagnostic tools, we will focus on the following overarching question:

What are the characteristics of hydrated carbonaceous asteroids and meteorites that have been subjected to space weathering processes?

This proposed systematic study will significantly enhance our understanding of how the spectral features indicative of hydrated asteroids are altered by space weathering. This knowledge will greatly increase the ability of scientists to use this spectral region for compositional analysis of hydrated asteroids, an approach that we anticipate will be even more common after the launch of the James Webb Space Telescope. Additionally, while this proposal is not focused on one specific asteroid, we anticipate that our study will yield information critical for interpreting data from remote sensing observations made of OSIRIS-REx and Hayabusa2 missions, which are targeting what are believed to be carbonaceous asteroids. Furthermore, this work is relevant to the Solar System Workings Program "as it seeks to understand processes that occur throughout the Solar System" and will consist of "laboratory studies that examine physical or chemical properties and processes" that may be important for the carbonaceous asteroids present in our Solar System.

Ahmed Mahjoub/Space Science Institute
Laboratory simulation of the composition of Titan's lakes in equilibrium with the atmosphere

We propose a combination of experimental measurements and theoretical modeling to constrain the composition of Titan lakes in equilibrium with the atmosphere. Since the discovery of Titan lakes by Cassini in 2006, interest in predicting their composition has grown substantially. The first attempted composition came from absorption bands obtained by the Cassini Visual and Infrared Mapping Spectrometer (VIMS), which showed ethane to be the major constituent in the southern Ontario Lacus while the strong absorption of the atmospheric methane prevents any detection of this molecule. Recent Cassini Radar data brought forth an echo from the lakes bottom, a low dielectric attenuation factor is needed within the lakes to explain these data, and it has been suggested that the lakes in the north are in fact dominated by methane, with little ethane present. Several thermodynamic models have been used to calculate the composition, and interestingly, their results on even the major lake components (methane, ethane, propane) exhibit large discrepancies, of tens of percents, from one model to another. These discrepancies strongly show the need for experimental laboratory data under realistic Titan conditions in order to better constrain the thermodynamic models. The experimental platform developed at JPL is the unique setup in the world allowing direct simultaneous measurement of both gas and liquefied hydrocarbons in equilibrium at the conditions of Titan's surface.

We will use the JPL Titan Lakes Simulation System, which has been designed and developed by the PI over the past years, to synthesize Titan Lake analogs. In this system, we can prepare a variety of mixtures of hydrocarbons (primarily methane, ethane, and propane) in the gas phase, and condense them under Titan-simulated conditions (1.5 bar nitrogen pressure, 92 K). A Gas Chromatograph is installed on the chamber, and will be used to measure simultaneously the composition of the liquids produced and the equilibrium composition in the headspace within the chamber. This study will provide the first direct measurements of both vapor and liquid compositions, in thermodynamic equilibrium. Experimental measurements will be used to constrain thermodynamic models, with the goal of improving prediction of the chemical composition of Titan lakes.

Michael Manga/University of California, Berkeley
Ocean-to-surface pathways on Enceladus

The ongoing eruptions of water at Enceladus' South Pole and possible eruptions on Europa may transport liquid water from a subsurface ocean to the surface and into space, where it may be sampled by future spacecraft. Understanding the processes that govern the ascent and fate of water on these bodies will inform our interpretation of future spacecraft observations and will provide fundamental new information about the state and evolution of the ice shells on Europa and Enceladus.

The proposed work addresses the mechanics of cracks, from their initiation to their freezing, using a combination of idealized analytical models and numerical thermomechanical models of deformation and heat transport. Specifically, we will address (1) under what conditions can cracks initiate at the surface, the base of the ice shell, or at intermediate depths? (2) How do fractures affect the temperature in the ice shell? Does tidal sloshing in fractures thin the ice shell locally, and if so, how does this promote or hinder additional cracking? (3) How do tidal sloshing, abrasion, and condensation promote or inhibit growth, closure, and localization of vents along fractures? (4) What surface features are expected to form adjacent to cracks?

The proposed work is relevant to the scope of the Solar System Workings program. Specifically, the advances in our understanding of cracks on icy moons will contribute to the SSW objective of "Identify objects with evidence of active or ancient tectonics and understand the processes and inputs that cause tectonic activity to start or stop. Understand the role that regional and global stress fields play in the formation of large-scale surface features and how those features inform studies of the global structure and dynamics." The proposed work also directly addresses the Planetary Decadal Survey question "Has material from a subsurface Europa ocean been transported to the surface, and if so, how?"

Jean-Luc Margot/University of California, Los Angeles
In-Depth Investigation of the Physical and Dynamical Properties of Asteroid Systems

We propose to characterize the physical and dynamical properties of near-Earth asteroid systems that have been observed at high spatial resolution and high sensitivity with Earth-based radar. Radar data sets provide an extremely powerful tool to characterize the physical properties of asteroids and the dynamical and radiative processes that govern their formation and evolution. Our investigation will elucidate the spin-orbit dynamics of asteroid systems, quantify their tidal and binary YORP (BYORP) evolutions, and provide additional insights into satellite formation and surface modification processes. In particular, we will put the hypothesis of BYORP evolution, which currently lacks solid observational evidence, to a stringent test with a high-quality data set that spans 18 years. Such a test is critical because of the wide-ranging implications of BYORP on the lifetimes and evolutionary pathways of asteroid systems as well as our understanding of the mechanical properties responsible for tidal evolution. In addition to quantifying spin states, shapes, masses, and densities, our investigation will enable probes of the thermal and mechanical properties of small bodies. Our specific objectives are: (1) To determine accurate shapes, spin states, masses, and densities of 66391 Moshup-Squannit (1999 KW4); (2) To determine the mutual orbit characteristics and evolution of the Moshup-Squannit system; and (3) To determine accurate shapes, spin states, orbits, masses, and densities of other asteroid systems. The proposed investigation is directly responsive to the goals of the Solar System Workings program, which seeks investigations that improve our understanding of orbital characteristics and evolution, interior structure, and modification of surfaces.

Molly McCanta/University of Tennessee, Knoxville
Experimental Constraints on Surface Weathering on Venus

With growing recognition of the multitude of Venus-like exoplanets (Zeng et al., 2016; Ostberg and Kane, 2019) and the rise and demise of liquid water on its surface over billions of years (Way et al., 2016), understanding of the evolution of Venus has gained paramount importance to studies of planetary habitability. On Earth, continents, geologic activity, subduction, and high heat flow are important to habitability (Höning et al., 2014; Hays et al., 2015; National Academies, 2018), but the extent to which these processes are active on Venus remains a missing link for rocky planet evolution.

Laboratory constraints are needed to interpret data from impending Venus missions that include NIR spectrometers: VERITAS (Smrekar et al., 2020), DAVINCI (Garvin et al., 2020), and EnVision (Widemann et al., 2021). Additionally, answers to questions regarding experimental kinetics of Venus surface alteration and its spectral signature are also critical to gaining an understanding of surface-atmosphere interactions resulting from chemical weathering on Venus. These are urgently needed to constrain modeling of atmospheric chemistry and relative ages of surface features. They require a multifaceted approach using integration of diverse perspectives and disciplines of study. This proposal seeks to undertake targeted experiments accompanied by careful kinetic modeling to generate fundamental laboratory data to answer questions related to reaction kinetics and surface spectroscopy. Objectives include:

1. Laboratory experiments at Venus temperatures to simulate interactions between igneous rocks and CO2-only and CO2/SO2-rich gas, using five different bulk compositions ranging from sub-alkaline tholeiites to alkaline rocks.
2. Acquisition of first ambient reflectance and then Venus-temperature emissivity spectra of those experimental samples at the unique Planetary Spectroscopy Laboratory at DLR Berlin, followed by additional reflectance measurements, to understand spectroscopic changes that occur with alteration.
3. Characterization of experimental samples at microscopic scales from the unaltered interior outward into unreacted rock, relating those changes in mineralogy and oxidation state to spectroscopic results, using transmission electron microscopy (TEM), Focused Ion Beam Scanning Electron Microscopy (FIBSEM), X-ray diffraction (XRD), and Mössbauer spectroscopy.
4. Use these results to evaluate alteration rates on Venus to constrain kinetics and place constraints on the age of the Venus surface.

These results will serve the goals of the Solar System Workings Program by addressing "the evolution and modification of surfaces." They will "characterize and understand the chemical [and] mineralogical& features" of the Venus surface by "developing theoretical and experimental bases for understanding" them… "in the context of the varying conditions through time after formation."

Franklin Mills/Space Science Institute
Simulating the spatial distributions of carbon monoxide and oxygen to better understand the chemical stability of Venus' atmosphere

The proposed research aims to improve and quantify understanding of the processes maintaining the chemical stability of carbon dioxide (CO2) on Venus by comparing the expected 3D upper atmospheric distributions of carbon monoxide (CO) and oxygen (O2) with observations.

The proposed research combines 3D simulations from the Venus Thermospheric General Circulation Model (VTGCM) and 1D diurnal-cycle simulations from the Caltech/JPL chemistry model (KINETICS) to determine the expected distributions of CO and O2 as a function of time-of-day and latitude that result from coupling transport and chemistry. The results will be compared with CO and airglow observations, provide a more realistic target for determining the still unknown abundance of ground-state O2, and quantify the magnitude and location of losses required to bring simulated O2 below the observational upper limit. Achieving a detailed understanding of Venus' current atmospheric chemistry and dynamics would enable more accurate simulations of Venus' evolution, past and future. Understanding the composition, dynamics, and evolution of planetary atmospheres are core themes of the SSW program.

CO2, the primary atmospheric constituent, photolyzes into CO and O at wavelengths ~< 200 nm [e.g., Ityaksov et al 2008, Inn and Heimerl 1971], and the observed night side O2 IR airglow confirms production of O2 from O [e.g., Gerard et al 2012]. If catalytic cycles did not enhance production of CO2 from O, O2, and CO, significant CO and O2 would accumulate [e.g., Nair et al 1994].

Even with known catalytic processes, simulated steady-state O2 abundances are a factor of 6-10 larger than the smallest observational upper limit [Marcq et al 2018], but almost all simulations have been 1D global-/diurnal-average, while the upper limits are from day side observations. The few 3D simulations of O2 also overpredicted O2 and had simplified chemistry [e.g., Lefevre et al 2019]. Observed CO profiles vary significantly with time-of-day and latitude [e.g., Clancy et al 2012] so it is likely O2 profiles also vary. Simulating time-of-day and latitudinal variations in O2 may be crucial for reconciling modeled O2 with observations.

CO and temperature at 120-150 km observed by the Visible and Infrared Thermal Imaging Spectrometer (VIRTIS) on Venus Express (VEx) agreed well with VTGCM simulations [Gilli et al 2015]. At 100-120 km near the subsolar point, however, VTGCM CO abundances were systematically smaller than those from VIRTIS-H, and VTGCM temperatures were up to 50 K warmer than those from VIRTIS-H [Gilli et al 2015]. Comparisons of CO2 photolysis rates as a function of time-of-day and latitude between VTGCM and KINETICS may assist in resolving this.

VTGCM has simulated the O2 IR, OH IR, and NO UV nightglow distributions in the Venus upper atmosphere, thereby providing model validation of the mean global circulation in the upper atmosphere [e.g., Brecht et al 2012; Parkinson et al 2021]. KINETICS has been used to study atmospheric chemistry on all solar system planets and extensively benchmarked against observations, analytical solutions, and other models [e.g., Michelangeli et al 1992; Zhang et al 2013].

The proposed research extends the current practice of using a global-/diurnal-average KINETICS simulation to determine reaction rates for VTGCM by using diurnal-cycle KINETICS simulations to inform VTGCM simulations and incorporating VTGCM results into KINETICS simulations as upper boundary conditions and atmospheric structure profiles. This enhanced modeling approach will enable exploration of more comprehensive interactions between chemistry and transport than is computationally feasible in a GCM that incorporates comprehensive chemistry.

Csaba Palotai/Florida Institute of Technology
Jupiter Impact Modeling

In 1994, the scientific community labeled the Shoemaker-Levy 9 (SL9) event as "once in a lifetime" because estimates indicated that we might have had to wait a century or more to observe another impact. In reality, it was only 15 years until a half-kilometer sized object left a big scar on Jupiter and overall nine jovian impact events were observed since 2009, with two occurring in the Fall of 2021.

We propose to carry out data analysis and numerical simulations for the SL9 and 8 other smaller impacts that occurred between 2010 and 2021 on Jupiter. The proposed work will enhance our knowledge of the impact phenomena and the structure, dynamics and energetics of Jupiter's atmosphere. The three scientific objectives for this project are as follows:

Objective1: How do impact parameters affect the light curves of jovian superbolides? We have successfully modeled the 2012 and 2019 impacts by 10m-sized objects (Hueso et al. 2013, Sankar et al. 2020). Certain parameters of the observed light curve were not matched adequately and we will investigate how varying the impact angle affects our results.
Objective2: Which impactor and atmospheric configurations reproduce the observed thermal and volatile abundance structure of the SL9 and 2009 impact sites? We will add different volatiles (e.g. NH_3, H_2O) to our Jupiter model and simulate the evolution of their three-dimensional structure following an impact event. We will quantify the mass of the displaced material and compare that to observations.
Objective3: How did the dark, slowly expanding rings form at the SL9 impact sites and how does the angle variation affect the ring formation? We will test currently available wave propagation models and test whether the impact perturbation couples efficiently to their suggested propagation mechanisms, and whether the resulting disturbances produce an effect that could be observed in in optical images. We will also explore the idea of the upwelling bubble as the potential source for the observed rings.

Groundwork for the proposed project has been laid down by our previous work. For our impact calculations, we will use the ZEUS-MP 2 hydrodynamic code that employs a moving grid that follows the impactor through the atmosphere. We have developed a remapping algorithm that enables us to carry out extended simulations and we also introduced volatiles into the model that will help us to determine the composition of the perturbed atmosphere. We will create self-consistent, end-to-end, composite simulations of various jovian impact events with reducing the assumptions of parameter values to a minimum. We will also employ a fragmentation code that successfully modeled terrestrial (Palotai et al. 2019) and jovian (Sankar et al. 2020) bolide events.

Erika Rader/University of Idaho, Moscow
GRIMLINS: Graphic Rheology In Molten Lava ImagiNg System

The GRIMLINS project will use experimental volcanology to examine the fundamental properties of molten lava in the visible to near-infrared (VNIR) with the goal of interpreting data from “lava worlds”, planetary surfaces dominated by volcanism, as well as volcanic eruptions on Earth. We propose to improve our ability to interpret the rheology and composition of these lavas by beginning a database of experimental molten basalt spectra. We will seed molten basalt flows with differing amounts of olivine, Fe-oxide crystals, and plagioclase, and collect hyperspectral images during cooling. Additionally, we will collect and quench samples of this material to analyze the petrology of the molten sample without the influence of temperature. Further geochemical compositions, surface textures, and vesiculation levels can then be tested using our protocol thus extending the spectral database of volcanic rocks into the molten to near-molten range.

Scot Rafkin/Southwest Research Institute
Constraining the Structure, Evolution, and Dynamics of Titan’s Atmospheric Boundary Layer

This will be the first study to explicitly simulate and characterize in detail the evolution of Titan's PBL, and this study is unique in its comprehensive treatment of PBL structure, processes, and dynamics. The Goal of the proposed investigation is to better constrain the structure, evolution, and dynamics of Titan's planetary boundary layer (PBL) as a function of season, location, and surface properties. The PBL is the lowest atmospheric layer and is critical to the exchange of mass, momentum, and energy between the surface and the atmosphere. Thus, the structure, evolution, and dynamics of Titan’s PBL is relevant to understanding numerous physical processes on Titan, including but not limited to:

- Volatile evaporation from damp regolith and lakes, and contributions to the global volatile cycle;
- Dunes and other aeolian formations, and waves upon lakes resulting from turbulent surface wind stress;
- Conversion of insolation to atmospheric heating through turbulent fluxes;

- Missions that descend through and operate on the surface or in the atmosphere (e.g., Dragonfly).

The Goal is achieved through completion of three Objectives with Associated Questions. The three Objectives are addressed through the technique of Large Eddy Simulation (LES).

Objective 1: Evaluate hypotheses for the thermal structure observed by the Huygens probe.
Q1: Can the LES results of Lavely et al. [2021] be reproduced?
Q2: How does the PBL at the Huygens landing site evolve over a diurnal cycle and are the results consistent with the hypothesis of Charney and Lebonnois [2012]?
Q3: How do changes in seasonal insolation and large-scale motion modulate PBL evolution at the Huygens Landing Site, and is there a residual, seasonal PBL top [Charney and Lebonnois, 2012]?
Q4: What is the impact of different regolith moisture on PBL evolution?

Objective 2: Validate Earth-based turbulence closure parameterizations used by mesoscale, cloud, and global circulation models.
Q5: What are the quantitative measures of turbulence on Titan and how do they compare to Earth?
Q6: How are turbulent properties related to bulk atmospheric properties?
Q7: How well do terrestrial turbulence closures represent turbulent processes on Titan?

Objective 3: Characterize and quantify the diurnal evolution and dynamics of the PBL.
Q8: What is the character of turbulent organization and what are the driving dynamics on Titan?
Q9: Do convective vortices or dust devils develop at eddy updraft intersections and how does genesis compare to theory [Jackson et al, 2020]?
Q10: What is the potential for aeolian activity on flat vs. dune-like terrain?
Q11: What conditions are likely to be encountered by spacecraft operating in the PBL?

The proposed is within scope of the SSW Program that includes research into atmospheric and climatological processes. Further, SSW invites investigations relevant to surfaces and atmospheres, and the proposed work bridges these two research areas. The study of Titan's PBL describes how mass, energy, and momentum are exchanged between the atmosphere and surface, and provides insight into aeolian activity. The LES technique is a type of numerical modeling investigation and is therefore compliant with the range of methods list in the SSW Announcement of Opportunity. With regard to relevant SSW research areas, the proposed effort falls squarely into the "Dynamics and Thermal Structure" category of "Planetary Atmospheres" and cross-cuts "Surfaces and Interiors" through the study of "Evolution and Modification of Surfaces".

Elizabeth Rampe/NASA Johnson Space Center

Investigating Formation Processes of Sulfate Salts: Implications for Ancient Aqueous Environments on Mars

Our understanding of the modification processes of rocks and soils on the surface informs our knowledge of the aqueous history of Mars. In turn, accurate interpretations of surface processes hinge on our ability to characterize surface materials' primary and alteration mineralogies and chemical compositions. The stratigraphic distribution of sulfate minerals in Hesperian over Noachian terrains observed via orbital and landed missions demonstrates the importance of these phases as indicators of a transition in the martian environment. Their unique distribution and importance for interpretations of martian climate change make characterizing sulfate salts synthesized under various environmental conditions critical for interpreting past environments on Mars. We speculate that many of these sulfates may have formed under cold and icy surface conditions. The overall objective of our study is to characterize the sulfate phases that form under cryogenic conditions and determine how to distinguish cryogenic sulfates from those that form under warmer conditions with instruments on orbital and landed Mars missions. We hypothesize that sulfate phases that form from cryogenic processes are distinct from those that form under warmer conditions. We can use this information to characterize better the ancient martian environments in which sulfates are found.

We will synthesize Mars common sulfates, including Mg-, Fe(II and III)-, Ca-, and Al-sulfate salts at cryogenic (-195 & -10ÚC), evaporative (25ÚC), and hydrothermal conditions (140ÚC). We will test our hypothesis that temperature strongly affects the precipitate phases' mineralogy, crystallinity, and hydration states by characterizing sulfates formed under variable temperatures with instruments similar to those on Mars missions (visible/shortwave-IR and Mössbauer spectroscopy, X-ray diffraction, evolved gas analysis, and deep UV Raman analysis). We will supplement our analysis from mission analog instruments with synchrotron near-edge X-ray absorption fine structure spectroscopy (NEXAFS) and transmission electron microscopy (TEM) analyses to characterize structures at the nanometer scale.

Our experimental design studies the effects of temperature on sulfate salts precipitated from both single and multi-component solution compositions. To reduce any possible transformations, samples will be prepared in small batches, characterized immediately after synthesis, and stored in humidity and redox-controlled environments. We will employ gentle heating at 60 ÚC to mimic conditions predicted for sample return from Jezero and at 150 ÚC to mimic burial diagenesis on Mars to evaluate stability of sulfates at elevated temperature. Additionally, diurnal freeze-thaw cycles will be conducted on the sulfate products to investigate possible alteration processes. We hypothesize that gentle heating and freeze-thaw cycles will mimic alteration processes on Mars and indicate the persistence of species and crystallinity of sulfate precipitates.

Our study will result in a detailed characterization of sulfates that form in extremely cold environments which are currently poorly understood. Our unique capability to apply an array of Mars-relevant instrumentations to study sulfates synthesized under a range of temperature regimes will aid in identifying signatures of cryogenic sulfates in Mars datasets. The timing of our proposed work is advantageous as Curiosity rover sits just below a sulfate-bearing unit identified from orbit, and data that we collect in this project could be used to interpret data measured by Curiosity and identify cryogenic sulfates in samples returned from Jezero crater. The data we collect will be disseminated to the scientific community through conferences and peer-reviewed publications and archived in the PDS Geosciences Node, facilitating other scientists to identify cryogenic sulfates in martian datasets.

Norbert Schorghofer/Planetary Science Institute
Subsurface Migration of Water Vapor on Airless Bodies

The interaction of water molecules with the lunar surface is a key process for the transport and sequestration of water. Recent observations suggest that a desiccated layer overlies a more hydrated layer on the Moon, for reasons that are yet unexplained, but may be related to subsurface migration of water molecules. Subsurface migration may also lead to net sequestration of H2O in the polar regions of the Moon, outside the permanently shadowed regions. Proposed here is the development of more sophisticated models of the migration of water molecules in the subsurface of airless bodies, with the objective of gaining a clearer understanding of sequestration and subsurface migration of water molecules on the Moon.

Methodology: An existing model of water vapor migration in the subsurface of airless bodies will be enhanced in several ways: a more sophisticated model of adsorption energies will be developed; the role of three-dimensional effects will be studied; and the diffusion model will be coupled to a thermal model based on measured surface temperatures. This comprehensive numerical model will then be applied to two aspects: 1) the concentration of adsorbed water with depth, and 2) the concentration of thermally pumped ice as a function of depth.

Significance: The proposed investigation is dedicated to the study of fundamental processes relevant for the search of water on the Moon. “Theoretical, analytical, and numerical modeling of physical or chemical processes” are within the scope of the program call. The primary focus of the proposed work is the lunar surface, where a multitude of observational constraints are available, but the results are also relevant to other large airless bodies, such as Mercury and Ceres.

Sven Simon/Georgia Tech Research Corporation
Ion Cyclotron Waves at Europa and Callisto

Based on a hybrid model (kinetic ions, fluid electrons) we plan to study the generation of ion cyclotron waves (ICWs) in the plasma environments of the Jovian moons Europa and Callisto. During their orbits both moons experience changes in the ambient plasma and magnetic field conditions by up to an order of magnitude, since their distances to the center of Jupiter's magnetospheric current sheet continuously vary. For different sets of magnetospheric upstream conditions we plan to determine the time scales for the growth of ICWs and the wave amplitudes associated with the major ionospheric pick-up species at Europa and Callisto. This analysis will allow the conversion of the ICW signatures observed during Galileo flybys E11 and E15 of Europa into mass loading rates, thereby constraining the plasma source represented by this icy moon. In addition, our results will provide an explanation for the absence of ICWs in magnetometer data from all Galileo flybys of Callisto, thereby enhancing our understanding of the moon's time-varying ionosphere. For this purpose, we will also compare the modeled properties of ICWs at Callisto to Cassini observations of ICWs at Saturn's largest moon Titan. The ambient magnetospheric plasma conditions at Callisto and Titan are extremely similar, and ICWs have been observed during only 2 out of 126 Titan flybys in the Cassini era. We will apply two different modeling techniques: (i) global simulations of the draped electromagnetic fields and deflected plasma flow near the moons to identify regions which are most susceptible to the growth of ICWs, and (ii) local simulations, with pick-up ions at a given production rate being injected into a uniform magnetospheric background plasma. Since ICWs allow to characterize atmospheric erosion based on magnetometer data alone, this will establish a comprehensive framework for constraining the dilute gas envelopes around Europa and Callisto. Our study will also support the planning of synergistic measurements during the Europa Clipper and JUICE missions.

The proposed study is directly relevant to the objectives of the Solar System Workings program element in the categories “Plasma interactions with structures and bodies”, “Sources and sinks of mass and energy” and “Magnetospheric processes and dynamics”, as described in section 1 (pages C.3-3 and C.3-4) of the announcement text. Especially, our study of Ion Cyclotron Waves at Europa and Callisto will make substantial contributions to “determine the mass and energy exchange with atmospheres and surfaces” and to “understand the physical and chemical processes that this coupling may drive”. By studying the generation of Ion Cyclotron Waves at Europa and Callisto, we will also make significant contributions to “characterize the neutral and plasma sources in planetary magnetospheres” and “describe the interactions between the magnetospheric plasma [...] and gas populations; characterize the energy flow and chemical processes within these coupled systems”. Therefore, the proposed project is relevant to the Solar System Workings program and thus, relevant to NASA.

Sven Simon/Georgia Tech Research Corporation
Pluto’s Induced Magnetosphere and its Interaction with Energetic Heliospheric Ions

By applying an established hybrid (kinetic ions, fluid electrons) model, we plan to study two important aspects of the interaction between the Pluto system and the solar wind:

(1) We shall investigate how Pluto's largest moon Charon interacts with the induced magnetosphere identified around the dwarf planet by the New Horizons (NH) spacecraft. Data from NH suggest that Charon mainly acts as a plasma absorber without an appreciable atmosphere. For various relative positions of Pluto and Charon, we will

investigate the deformation of Charon's wake when exposed to the non-uniform plasma flow in Pluto's solar wind interaction region.

Since the gyroradii of pick-up ions from Pluto's ionosphere exceed the radius of the dwarf planet by several orders of magnitude (and are even larger than the distance between Pluto and Charon), Pluto's induced magnetosphere possesses pronounced asymmetries, with dense plasma populations of Plutogenic origin confined to characteristic sectors of the magnetosphere. Therefore, Charon encounters a wealth of different plasma environments along its orbit, the interaction of which with the moon is yet to be explored. We will also investigate a possible feedback of Charon on the structure of Pluto's induced magnetosphere.

While the interactions of a plasma-absorbing moon with a super- or submagnetosonic plasma flow have been modeled before (e.g., at Earth, Jupiter, and Saturn), such studies usually apply a “local” approach, i.e., the incident plasma flow is assumed to be spatially homogeneous and any large-scale feedback of the moon's plasma interaction on the magnetosphere of its parent planet is neglected. The Pluto-Charon system provides a unique opportunity to study the influence of deviations from this “ideal” picture on the moon's plasma interaction process.

(2) By combining the electromagnetic field output from the hybrid model with an existing tracing tool for energetic particles, we will study the interaction of Pluto's induced magnetosphere with energetic heliospheric ions. Although the gyroradii of energetic ions exceed the radius of Pluto by more than two orders of magnitude, NH observations found the interaction of these ions with the dwarf planet's induced magnetosphere to be surprisingly strong: a broad and extended depletion region was identified at Pluto's wakeside. For various energies of the incident heliospheric ions, we shall systematically analyze the deflection mechanisms that lead to the formation of such a pronounced rarefaction region downstream of Pluto. In addition, NH identified periodic variations in the intensity of the energetic ion flux at Pluto's wakeside. We shall investigate whether these observed periodicities can be explained through particle deflection in the field of bi-ion waves downstream of Pluto, generated by the overlapping flows of solar wind and newly generated ionospheric pick-up ions.

This effort will result in the first comprehensive model of the interconnection between Pluto's thermal and energetic plasma environments.

The impact of this project would be a substantial improvement in our understanding of the interaction between the Pluto-Charon system and the solar wind. For the first time, we will rigorously constrain the contribution of Charon to the plasma and magnetic field perturbations within Pluto's magnetosphere. This effort will drastically enhance our understanding of fundamental physics in a unique type of magnetosphere that is occupied by two bodies of comparable size and, most importantly, that is heavily affected by ion kinetic effects. Besides, we will provide a comprehensive picture of the interconnection between Pluto's thermal and energetic plasma environments. This will reveal the mechanisms that led to several surprising observations by the NH spacecraft, namely the strong deflection of energetic heliospheric ions around Pluto, and the quasi-periodic patterns seen in energetic ion intensities downstream of Pluto.

Michelle Thompson/Purdue University
An Experimental Investigation of Space Weathering Processes on the Surface of Mercury

The surface environment at Mercury is unlike any other planetary body in the inner solar system, exhibiting low Fe content, high S content, and high carbon abundances. These chemical signatures point towards a planet that formed under highly reducing conditions and which hosts a volatile-rich mineralogy. Both of these characteristics are unique to Mercury and vary significantly from other, well-characterized inner solar system bodies. Further, the intensity of solar wind irradiation and the flux and velocity of micrometeoroids impacting the surface are both significantly higher at Mercury than at planetary counterparts at distances >0.38 AU. This scenario creates an extreme environment for space weathering, the surface process that operates across airless bodies and is driven by solar wind irradiation and micrometeoroid impacts. Space weathering causes significant changes to the microstructure, chemistry, and optical properties of surface materials. Knowing the effects of space weathering is critical for disentangling its contributions to spacecraft remote sensing data. Our understanding of space weathering processes across the inner solar system is largely based on decades of research on lunar soils. Studies of these samples identified Fe-bearing nanoparticles (npFe) as the source of the observed modified optical effects. More recent studies of samples from asteroid Itokawa and experimental simulations of space weathering of carbonaceous chondrites have further expanded the inventory of potential nanoparticle phases to likely include Fe-sulfides, Fe-oxides and Fe-Ni-S particles. The presence of these mineralogically diverse and optically active particles results in changes to sample spectral properties which do not conform to traditional lunar-style space weathering. The compositional variety of these nanoparticles is directly linked to the mineralogical complexity of the target material. While we have a firm understanding of how space weathering processes operate on the Moon and S-type asteroids, these bodies are exposed to less extreme conditions and have surface compositions which diverge significantly from what we expect on Mercury.

Though the MESSENGER mission revolutionized our understanding of Mercury, there remain fundamental outstanding questions about the nature of the planet. Vital among these unknowns is a detailed understanding of the active space weathering of Mercury and how these processes manifest in the chemical, microstructural, and optical characteristics of surface material. In order to interpret properly the data from the successful MESSENGER mission as well as maximize the science return from the BepiColombo mission, we must investigate the effects of space weathering on the surface of Mercury in the laboratory. We will use coordinated analytical techniques to determine changes in the optical properties, microstructure, and composition of samples exposed to simulated space weathering. For the first time, we will use materials prepared experimentally which are compositionally analogous to mineral phases expected on the surface of Mercury. In Task 1, we will investigate the effects of solar wind exposure by using H+ and He+ ion irradiation experiments to simulate the solar wind energies, fluences, and exposure timescales relevant for Mercury. In Task 2, we will simulate micrometeoroid bombardment on these materials using pulsed-laser irradiation to mimic the rapid high-temperature effects associated with impact events. In Task 3, we will use our sample observations to inform on the spectral changes we observe through radiative transfer modeling. This multifaceted approach addresses a critical knowledge gap in our understanding of space weathering processes across the inner solar system by focusing on the harsh conditions and unique surface compositions of Mercury.

PLANETARY DATA ARCHIVING, RESTORATION, AND TOOLS PROGRAM
Abstracts of selected proposals
(NNH21ZDA001N-PDART21)

Below are the abstracts of proposals selected for funding for the Planetary Data Archiving, Restoration, and Tools (PDART) Program 2021. Principal Investigator (PI) name, institution, and proposal title are also included. On November 23, 2021, seventeen (17) proposals were received in response to this opportunity and four (4) proposals were selected for funding. On August 3, 2022, thirty-five (35) proposals were received in response to this opportunity and seven (7) proposals were selected for funding.

Martin Barmatz/Jet Propulsion Laboratory
Dielectric Permittivity and Magnetic Permeability Measurements on Likely Venus Surface Materials

Scientific Goals and Objectives: We propose a three-year study to conduct and archive measurements of the dielectric permittivity and magnetic permeability of a variety of Venus-relevant geologic materials at frequencies near those used by the radar instruments on the Magellan Venus Radar Mapper" (S-band) at the Venusian surface temperature. Our measurements extend significantly past the current state of knowledge (Campbell and Ulrichs, 1969; Ulaby, Moore, and Fung, 1986) and are needed for the community to constrain properties of Venus' surface including first order estimates of composition and mineralogy.

These measurements of high-frequency (GHz) electrical properties will enable improved geologic model development by constraining the interpretation of emissivity and backscatter data from the Magellan S-band radar and passive microwave radiometry datasets, such as the GEDR (Global Emissivity Data Record), as well as potentially for the Venera 15/16 multi-frequency microwave radiometry datasets. Results will also be useful in a radar propagation-scattering model to compare with existing 12.6-cm (S-band) Magellan SAR data, which can be used to address the question of what geologically plausible materials contribute to the enigmatic high-backscatter surfaces of Venus. Further, this data could also be used to interpret data sets from previous and future missions yielding new insights into surface-atmosphere interactions, density and compositional heterogeneities within the crust, ages of lava flows, or different surface weathering regimes.

This work is timely with the renewed interest in Venus as evidenced by the selection of NASA's VERITAS and DAVINCI and ES'A EnVision missions. The proposed measurements will also be useful for planning these future experiments on Venus surface missions.

Methodology: The bulk of the experiments and analyses will be performed using JPL microwave resonant cavities and furnace facilities. We will use a standard cavity perturbation technique, one of the most accurate approaches, to determine a relevant sample's dielectric permittivity and magnetic permeability (as per Magellan S-band SAR and altimeter RADAR) at relevant Venus temperatures (460°C). We plan to study rocks and minerals that plausibly compose the crust of Venus, based on radar measurements and geodynamical models. Ancillary characterization of our samples beyond permittivity will include density and mineralogy and will be done using existing laboratory equipment at LPI, Wesleyan, and JPL. All data produced in this study will be published in the PDS in convenient tabular format.

Relevance: This research is directly relevant to the Planetary Data, Archiving, Restoration and Tools (PDART) program, as it is a laboratory study that will result in an archived product that will directly enhance the value of planetary surface data, particularly datasets relating to Venus, increasing the value of Magellan and other Venus radar products (USSR Venera 15/16). All planetary spacecraft data from Magellan have been available since the mid-1990s, and thus satisfy the PDS release requirement.

Shoshanna Cole/Space Science Institute
Mars Exploration Rovers Portal to Observations, Resources, and Tools to Advance Legacy Science (MER PORTAL)

Objectives:

The Mars Exploration Rovers (MER) mission was the first long-duration surface exploration of another world: Spirit and Opportunity roved Mars for 2210 and 5111 sols (martian days), respectively, accumulating a total of 20 years of daily data from multiple instruments. Researchers who want to analyze MER data but lack a connection to the mission often have difficulty both finding data and understanding the context and caveats of the data they do find. The proposed work would remove these barriers by creating software for a science-based search with the capability of downloading selected data from the PDS; metadata including science content, data quality indicators, and data acquisition contextual information; User Guides; data visualization tools; and links to existing tools and websites.

Methodology:

The proposed effort will develop the MER PORTAL software and catalog data from Spirit Sols 1-710. It will consist of 6 tasks:

1) Creating a MER PORTAL website that will be a single point of entry for access to MER data, resources, and tools; a database to house the metadata we produce in Tasks 4 and 5; and a user-friendly search interface to enable users to search our database and acquire data products from the PDS;
2) Developing data exploration and visualization tools to support users as they conduct their searches;
3) Writing User Guides, based on interviews we will conduct with MER team members, preserving information akin to the guidance one would give one's

graduate students. In addition to data analysis guides, we will produce guides summarizing the MER vehicle and instruments.

4) Examining MER images visually and with automated classifiers to create metadata that indexes their geologic, atmospheric, and rover-related content (e.g., outcrops, ripples, bright soil, dust devils, the rover deck, etc.). The content we index will be derived from the results of a survey of potential MER data users that we have already conducted.
5) Indexing data acquisition contextual information and data quality indicators for data products from all of the rover's instruments, enabling workers to search for data products relevant to and appropriate for their analyses. Some of this information can be found in the data products' PDS labels, filenames, or another database; we will index these automatically and utilize mission planning documentation and tools on the MER Analyst's Notebook for the rest.
6) Assembling annotated bibliographies of existing tools and websites relevant to MER data analysis and the MER mission.

Relevance:

This proposal addresses the PDART objective "to increase the amount...of digital information&available for planetary science research and exploration" and will "produce tools that would enable or enhance future scientific investigations." It is responsive to 3 sections of the PDART program element:

- Section 1.4 "Reference Database Creation"
Our reference database will enable researchers to conduct science-based searches for data products relevant to and appropriate for their analyses. The metadata we produce and that will be associated with data products in Tasks 4 and 5 will augment the metadata produced by the mission team.

- Section 1.5 "Generation of New Reference Information"
The User Guides we produce in Task 3 will be reference materials that will enable novice MER researchers to learn how to analyze MER data.

- Section 1.7 "Software Tool Development and Validation"
The MER PORTAL website search function will interface with our reference database and MER data products on the PDS, enabling science-based searches of MER data and retrieval of data products matching search criteria. The tools we produce in Task 2 will enable visual inspection and comparison of spectral data; mapping of compositional class, named rocks and soils, and data products' acquisition locations; and searches of MER data by Sol (day of mission), Earth date, time of sol, and solar longitude.

Christopher Edwards/Northern Arizona University
Improving Thermal Model Capability for the Planetary Science Community

We propose to improve a well-established, open-source 1D thermal model (KRC; K for conductivity, R for density (Á, rho), and C for specific heat the three terms in thermal inertia I.) commonly used for surface science and NASA programmatic tasks with broad applicability to numerous planetary bodies. Generally, thermal models used for temperature data analysis and regolith characterization (grain size, rock abundance, internal layering, cementation, presence of ices, etc.) do not include important forcings (radiative effect of clouds, circulation-driven heat sources, projected shadows from complex topography and eclipses, etc.). As a result, the full potential of rich temperature datasets cannot be fully exploited. Our proposed modifications would enable KRC to include a state-of-the-art atmosphere, ingest precomputed general circulation model (GCM) atmospheric inputs, and allow fully customizable forcings (downwelling visible/infrared radiances). These modifications to KRC would enable significant scientific advances across the solar system, as well as improve its capability to support landing site assessments and traverse planning for landed assets.

Planetary surface temperatures are frequently measured by instruments on landers /rovers/orbiters and provide an excellent means to quantitatively constrain the physical nature of near-surface regolith and inform the understanding of past and present geophysical processes. While the availability, diversity, and potential of remotely sensed temperature data increases continuously, dedicated numerical tools enabling the interpretation of that data for planetary regolith characterization still lag behind the state-of-the-art, especially the atmospheric (when appropriate) and environmental treatment. As a result, numerous science questions are not answerable and programmatic tasks (including landing site characterization and certification) are not always performed satisfactorily.

We propose to enhance and expand the capability of a well-established planetary regolith thermal model (KRC [6]) and facilitate its access for data analysis to the broader planetary science and engineering communities. To do so, we will:

1. Generalize the atmospheric treatment of KRC to make it applicable to any atmospheric condition of gas composition, pressure, dust or ice opacity, and able to ingest complex pre-computed GCM-derived quantities;
2. Enable the inclusion of arbitrary pre-calculated surface forcing relevant to planetary bodies, including transient topography-induced shadows, radiative contribution from nearby complex topography, excess heat brought by circulation processes, emission/reflection from surface asset, etc.;
3. Validate, distribute, and facilitate the use of KRC by a wide community through a number of interfaces tuned to the skill level and needs of the potential user.

Our goals and objectives will be achieved through the following tasks:

1. The modification and improvement of KRC's Fortran code base;
2. The validation of these model improvements following a rigorous methodology;
3. The archiving and distribution of the KRC code set through established archival tools;
4. The development of user-friendly tools (pre-coded functions, JMARS interface, click-and-drag compiled model build) facilitating the use of the model by a wide range of users.

Richard French/Wellesley College
Archiving and Tools for Radio Science Ring Occultations at Saturn and Uranus

The key objectives of this proposal are:

(1) to archive scientifically valuable Voyager and Cassini radio science (RSS) ring occultation data of Uranus and Saturn that are currently missing from the Planetary Data System (PDS)

(2) to host well-documented open-source tools on NASA's Planetary Science GitHub to enable scientists to understand and reproduce the complex steps required to go from raw observations to the archived intermediate and final scientifically useful results.

(3) to develop a common PDS4-compliant framework for current and future spacecraft RSS derived ring data

Currently, the PDS Ring-Moon Systems Node (RMS) contains diffraction-corrected RSS radial profiles of Saturn's rings from the Voyager 1 and Cassini missions, and of the Uranian rings from the Voyager 2 encounter, but not at the highest achievable (SNR-limited) resolution. Completely missing from the PDS is an entire category of valuable RSS derived data: the so-called scattered signal" that originates from the scattering of the transmitted radio signal by ring particles within the main lobe of the spacecraft's high-gain antenna beam. The time history of the scattered signal spectra at multiple wavelengths provides a unique probe of particle sizes and internal ring structure. Additionally, none of the derived RSS ring data in PDS are archived under PDS4 standards.

We propose to extend the scientific value of the PDS RSS ring archives:

1) We will design and implement a uniform PDS4-compliant archive structure to accommodate both the highest achievable resolution radial profiles and scattered signal spectrograms from Voyager RSS observations of Saturn and Uranus and Cassini RSS observations of Saturn.

2) Using this framework, we will archive intermediate geometry and calibration information, and final reduced products, for the following data sets:

a. The Voyager 2 Uranus X-band (3.6 cm) ring occultation at an effective radial resolution of 20 meters (compared to the 50 m processing resolution currently on the PDS), and radially resolved power spectra of the scattered signal, not currently available for any RSS data set.
b. The Voyager 1 Saturn RSS radially resolved power spectra at S-band (13 cm) and X-band, and independently processed high-resolution X-band radial profiles of the rings

using our current knowledge of Saturn's ring geometry and our open-source diffraction-reconstruction code, described in Task 3 below.
c. Cassini RSS S-, X-, and Ka-band (0.9 cm) radially resolved power spectra for selected observations early in the mission, preparing the way for a future archive of the complete set of power spectra for the entire Cassini mission.
d. Cassini RSS X- and Ka-band radial profiles for selected observations, at higher resolution than currently available on the PDS.

3) For each archived data set, the complete data processing pipeline to go from raw data to each intermediate and final archived product will be hosted on NASA's Planetary Science GitHub in the form of open-source Python and C-based code and accompanying scripts. Here, we will draw on many of the software tools we have developed for analysis of Cassini RSS data that are already on GitHub at https://github.com/NASA-Planetary-Science/rss_ringoccs.

4) We will produce data and software User Guides that document the products produced by this proposal and the steps and algorithms used to process the data.

Each proposed task is directly relevant to the objectives of the PDART program as described in Section C4 to increase the amount and quality of digital information and data products available for planetary science research and exploration, and to produce tools that would enable or enhance future scientific investigations." While our proposal includes the processing of Cassini data, our scope does not include the scientific analysis of Cassini data, and thus does not fall within the scope and objectives of the Cassini Data Analysis Program.

Michelle Kirchoff/Southwest Research Institute
Building Global and High-Resolution Regional Crater Databases for Ceres

Background and Significance
As is typical for other large main belt asteroids, Ceres' surface shows a geological history dominated by impact cratering. Due to lack of direct geological sampling, these craters provide the primary means to study the geological evolution of surface features and terrains. For instance, Ceres' surface shows evidence of recent localized geophysical activity based on low superposed crater density (e.g., Cerealia-Venalia faculae, Ahuna Mons). Furthermore, the influence of Ceres' volatile content, including near surface ice, on the evolution of the surface is most unambiguously recorded in the degradation and lack of large craters and basins (Bland et al., 2016; Marchi et al., 2016). Thus, in order to further advance understanding of Ceres' geological evolution, a robust global crater catalog for diameters (D) down to 1 km and high-resolution regional catalogs for features of interest are required. However, while individual global and regional crater counts have been published (e.g., Marchi et al., 2016; Hiesinger et al., 2016; Ruesch et al., 2016; Gou et al., 2017; Neeseman et al., 2019), no comprehensive global database and high-resolution regional crater databases of features of universal interest that could be used by any researcher have been produced.

Objectives and Methodologies

Our objectives are to i) build a master global crater database for D e 1 km and ii) build 3-5 regional master crater databases for features of universal interest on Ceres for D e 10s-100s of meters (depending on available image resolution). The proposed work will tackle these goals in two tasks. In Task 1, we will start with published preliminary, individual crater catalogues (e.g., Marchi et al., 2016; Hiesinger et al., 2016; Gou et al., 2017, Zeilnhofer and Barlow, 2021). Data from these catalogues will be validated using the latest Low Altitude Mapping Orbit Dawn Framing Camera (FC) image global mosaics (~35 m/pixel), along with available global and regional DTMs. We will then add crater measurements as necessary using these datasets to complete the database. To ensure full utility for as broad as possible scientific research goals, the database will record location, size, morphology (e.g., simple, complex, primary, secondary), morphometry, preservation state, and confidence that a feature is a crater. We will also record if the crater has other interesting aspects, such as interactions with fractures, unique ejecta, flow-like features, etc. We expect the final global database to have ~60,000 craters with D e 1 km. In Task 2, we will use the highest resolution imaging of selected features of universal interest to compile regional crater databases in and around those features for 10s-100s m < D < 1 km. Our initial selection of features includes Coniraya crater (relaxed), Ernutet crater (associated organics), Haulani crater (associated organics). Each of these are covered by higher resolution Low Altitude Mapping Orbit FC images and DTMs that will allow additional crater counts down to at least a few tens to hundreds of meters (pixel scales from 3-35 m/pixel). Each feature will result in a different number of craters cataloged depending on age and minimum diameter, with a maximum of ~10000 expected for the oldest terrains. All the data used in this proposal is available through the PDS at the time of writing. The resulting crater catalogs will be archived in The Annex of the PDS Cartography & Imaging Sciences Node.

Kevin McGouldrick/University of Colorado
Completing the Archiving of the Pioneer Venus Orbiter UV Spectrometer Data Set

We propose to submit for archival with NASA's Planetary Data System (PDS) Atmospheres Node, the complete Pioneer Venus Orbiter Ultraviolet Spectrometer (PVOUVS) data set that was collected over a nearly 14-year time baseline between December, 1978 and October, 1992. This archive would consist of Level 1 (raw telemetry and orbit attitude) data products, Level 2 (observations calibrated to radiance units, and observing geometries) data products, and Level 3 (spectrally-resolved albedo maps) data products. The proposed work is especially timely, as observations of Venus in ultraviolet wavelengths are currently being made (December 2015 -- present) by JAXA's Akatsuki mission Ultraviolet Imager (at 283nm and 365 nm), and will soon be made by the Compact UV/Visible Spectrometer (CUVIS) instrument on the Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging (DAVINCI) mission, recently selected by NASA for launch to Venus in the late '20's. Such missions build upon previous observations made by the Venus Monitoring Camera (VMC) on Venus Express (at 365 nm) from April, 2006 through November, 2014). Archiving this data set in the PDS will enable access to a time series of observation of Venus at ultraviolet wavelengths spanning five decades (December, 1978 through present -- 42.5

years, as of the submission of this proposal), with the possibility of further extension of this time baseline by the still-operational Akatsuki spacecraft, and the pending DAVINCI mission.

That is, the proposed effort has three main objectives:
1. Make the PVOUVS dataset available to the scientific community as soon as possible as a PDS3-compliant archive.
2. Generate added value to the existing dataset by generating Level-3 derived data products that are of particular interest to the Venus science community.
3. Update the archive to a PDS4 archive to ensure long-term preservation of the dataset so that it is compliant with modern standards.

Ryan Ogliore/Washington University
A Database of Online Gigapixel Compositional Maps of Primitive Meteorites

Key Objectives: This proposal seeks funding to acquire digital compositional maps, at extremely high spatial resolution, of 42 meteorite samples. These maps will be used by planetary scientists to compare the asteroid samples returned by space missions (NASA's OSIRIS-REx mission and JAXA's Hayabusa2 mission) to types of meteorites that are thought to be similar. This will allow for "comparative asteroid mineralogy" where scientists will be able to link the returned samples to meteorites with the goal of establishing a common, or distinct, origin and history.

Methods: The methods to acquire and display these gigapixel maps (backscattered electrons and X-rays) have already been developed. The sample is scanned at high resolution using a "focus map" approach in the electron microscope, images are stitched and assembled using a combination of Python, Matlab, and the vips astronomical image processing package. An image pyramid is created for each imaging modality, which are registered to each other. The images then are displayed using OpenSeaDragon, with various web-based tools to help the researcher investigate the sample.

Significance: The proposed database of maps will allow a greater science return for NASA's OSIRIS-REx mission, as well as JAXA's Hayabusa2 mission. The first question that will be asked when these new samples are analyzed is: "Have we seen this sample before?". To answer this question, we must compare with known meteorites, which have been studied extensively over the past several decades. However, many scientists do not have easy access to meteorite samples or the tools to study them at small scales. This database will provide a set of samples that can be used for comparative study with the returned asteroid samples. The proposed database can be used for machine learning projects, a promising but mostly unexplored venue in sample science, which require a large number of training images.

Nathaniel Putzig/Planetary Science Institute
MARSTHERM 2.0: Enhanced Thermophysical Analysis Tools for Mars Research

The Planetary Science Institute hosts MARSTHERM (marstherm.psi.edu), a public interface to numerical thermal modeling and thermal-inertia derivation codes that have been used extensively for global, regional, and local studies of Martian thermophysical properties. MARSTHERM provides forward modeling of surface and brightness temperatures, mapping of apparent thermal inertia (ATI) as derived from observations by the Mars Global Surveyor Thermal Emission Spectrometer (TES) and the Mars Odyssey Thermal Emission Imaging System (THEMIS) in user-specified areas of interest, and comparisons of seasonal variations of ATI as calculated from a fixed set of pre-calculated two-material models with those from TES data in the areas of interest. These comparisons enable the assessment of material heterogeneities (layering, horizontal mixtures at sub-pixel scales) that may be present. MARSTHERM was developed under a 2010 Mars Fundamental Research Program (MFRP) grant and was maintained through Sep. 2020 with a modicum of funds from the Mars Subsurface Water Ice Mapping (SWIM) project [Morgan et al., 2021; Putzig et al., 2020; Putzig et al., in press].

We propose to enhance MARSTHERM by augmenting its computer hardware with an additional server, making improvements to the thermal modeling and thermal-inertia derivation codes, and upgrading its web interface and functions. Our code improvements will include porting of an existing multilayer FORTRAN-90 subsurface thermal model and a state-of-the-art 1-D atmospheric thermal model to Python 3+, as a means to increase the future pool of collaborators and facilitate integration with the web interface. Our changes will provide new capabilities to MARSTHERM that include the option of specifying up to five layers of distinct subsurface materials and the use of temperature-dependent conductivity in the subsurface. We will also port the existing FORTRAN-77 thermal-inertia derivation code to Python 3+ and generate a new 10-dimensional lookup table that allows two layers of distinct materials as well as variable dust- and water-ice opacities. The new derivation code and lookup table will be used to generate a library of heterogeneity-model output for comparison to TES and THEMIS results. Beyond the integration of new modeling and derivation codes, we intend to provide other upgrades to the web interface such as (1) mosaicking of THEMIS ATI images within areas of interest, (2) porting of the website driver software from Python 2 to Python 3+, and (3) general modernization of the user interface. In addition, we will conduct benchmark" analyses comparing the two most widely used models (MARSTHERM and KRC) for analyzing thermophysical data from Mars, and we will publish those results as a publicly accessible database.

The proposed work is of direct relevance to the PDART program for several reasons. MARSTHERM currently provides a publicly accessible interface that allows higher-order analysis of TES and THEMIS data and enables users to run widely used numerical thermal modeling code. Over 140 researchers around the world access these data and tools, with new users signing into the system on a monthly basis. The work proposed will increase the quality of MARSTHERM tools and further broaden their availability and usefulness for planetary science research and exploration, thereby enhancing future scientific investigations. Apart from that needed for code verification purposes, no analysis, interpretation, or product generation for spacecraft data is included in the proposed work. Appropriate codes will be delivered to NASA's GitHub repository.

Stuart Robbins/Southwest Research Institute
Fully Controlled Context Camera Data for Mars: New SPICE Data and Global Mosaics

Background: The community of NASA-funded and international researchers who study Mars is large, and significant data have been returned from spacecraft observing the planet. Many types of investigations of Mars rely on studying its surface through images taken by orbiting craft. Such investigations are greatly assisted by the availability of high-quality, high-resolution mosaics of the surface. The Context Camera (CTX) aboard the Mars Reconnaissance Orbiter (MRO) has taken H5 6 m/pixel visible light images of almost the entire surface of Mars at consistent lighting and pixel scales for the past fifteen years. Despite these qualities, the CTX dataset has not yet been publicly fully controlled and a mosaic made from those controlled images.

Goals & Objectives: Our first objective is to create a global set of fully controlled SPICE data for the CTX dataset. (Fully controlled means that each image pixel is in the correct location both relative to other images' pixels and on the surface as referenced to another controlled dataset, like MOLA.) Our second objective is to create a mosaic from the fully controlled data. The first objective would allow researchers to process their own CTX images with our updated kernels, which will greatly enhance others' research that requires multiple images, such as creation of digital terrain models and detection of changes on the Martian surface from dunes, new craters, or other processes. It would also allow any other dataset taken contemporaneously (such as HiRISE and CRISM) to be better controlled because we would be updating the spacecraft kernels. The second objective would provide an important product for the Mars research community for innumerable studies, a base map for the Mars cartography and geologic mapping communities, and a fully controlled reference for even higher resolution data such as HiRISE and CaSSIS.

Approach & Methodology: We divide the planet into regions based on the historic 30-division Mars Charts (MC). Our approach to controlling data is a mixture of fully automated steps mixed with manual efforts. The automated work is done through Python scripts that drive the USGS's Integrated Software for Imagers and Spectrometers (ISIS); we use Python v. 3.6 and 3.8 for different parts, and ISIS v. 4.3.0 on Linux and 4.4.0 on MacOS. Creating a fully controlled dataset starts with creating, via automated tools in ISIS, a control network which is a system of links between pixels of the same feature on different images. Manual effort comes in to validate the network, fix mistakes, add points where needed, and tie some of the links to a ground source (MOLA and the public fully controlled THEMIS mosaic). After a network is made, ISIS tools output updated spacecraft and camera data (our first objective). The updated data are then used to project the images and create a mosaic (second objective). During this process, we correct for several known but rarely corrected photometric issues with the CTX data, including the darkening at the edges, manually adjust the mosaic order to ensure the best images are "on top," and perform a cosmetic control process we developed to produce an even-looking mosaic.

Relevance: Our proposal fits directly into section 1.2 of PDART AO, the creation of a higher-order data product (the mosaics and SPICE data); and section 1.5, generation of new reference information (SPICE data as well as a controlled mosaic that can be used as reference for other datasets or investigations). This work is only to create that product, it contains no hypothesis-based science, so it is relevant to PDART and not to other programs such as MDAP. Data would be archived with the PDS Cartography & Imaging Node at USGS.

Thomas Stephan/University of Chicago
Preserving, correcting, maintaining, and further developing the Presolar Grain Database

Introduction. Presolar grains, found in primitive meteorites, interplanetary dust particles, cometary samples, and likely in samples returned from asteroids Ryugu and Bennu, condensed in the winds of evolved stars and in the ejecta of stellar explosions and therefore represent samples of stardust that can be analyzed in the laboratory. They exhibit large isotopic anomalies in major and minor elements, which can be used to link them to their origins, stars predating our Solar System. Presolar grains are of great interest to isotope cosmochemists and to astrophysicists alike, since they sample some of the least altered major building blocks that formed our Solar System and provide direct insights into nucleosynthetic processes occurring in evolved stars as well as mixing processes in the early Solar System. Isotopic analyses of presolar grain measurements are therefore complementary to astronomical observations.

Since presolar grains were first isolated from meteorites about three decades ago, many thousands of individual grains have been analyzed for their isotopic composition, often in an automated way to facilitate the search for rare and exotic grains.

The Presolar Grain Database (PGD), a collection of spreadsheets containing the vast majority of isotope data (published and unpublished) on presolar grains, was first released in 2009. The PGD was initially compiled by students at Washington University in St. Louis and occasionally updated and corrected over the years, but it has become apparent that accumulated errors have compromised major parts of the PGD.

At the Presolar Grains Workshop in Chicago in 2019, the future of the PGD was discussed. Since the PGD has been used as a helpful tool by many researchers in cosmochemistry and astrophysics, we decided to rebuild the PGD from the ground up by: (1) eliminating known errors; (2) searching for inconsistencies by comparing with publications, original data files, and/or personal compilations; and (3) updating and adding data that have been reevaluated and/or published.

Our initial effort focused on silicon carbide (SiC) grains, the type of presolar grains that has been studied the most. Currently, we have corrected isotopic data for exactly 19,976 presolar SiC grains, which can be found on the Washington University in St. Louis website https://presolar.physics.wustl.edu/presolar-grain-database/.

Goals and Objectives. We propose to continue our efforts about preserving, correcting, maintaining, and further developing the PGD. There are probably a few hundred SiC grains that have been analyzed and whose data have not made it into the PGD yet. Data for other grain types than SiC, e.g., graphite, silicon nitride, oxides, and silicates, have not yet been examined and need to be thoroughly scrutinized and double-checked against original data files and published data tables.

In addition to providing large data tables, we propose to make the data more accessible by developing and providing software tools that can be used to sort and extract data from the PGD with user-defined parameters. All data and tools will be available to the entire scientific community, archived in the NASA Planetary Data System (PDS), and is expected to be the main reference for presolar grain data for cosmochemists and astrophysicists for the foreseeable future.

Relevance. The proposed work is highly relevant to the goals of the Planetary Data Archiving, Restoration, and Tools (PDART) program as it will generate a higher-order data product, archive data sets, create a reference database useful for planetary research, and develop software tools.

Kathryn Volk/University of Arizona
Tools for Advanced Dynamical Characterization of Solar System Small Bodies

Motivation: We will soon enter a new era of solar system small body science when LSST increases the number of known solar system small bodies by over an order of magnitude. Dynamical analyses of small bodies have led to many important insights in planetary science. The dynamical evolution of an observed small body's orbit can place it into context as, for example, a likely primordial small body whose orbit has remained largely unchanged since formation (like the New Horizon's target Arrokoth); similarly, dynamical evolution marked by rapid changes can indicate an object belongs to a short-lived, transient class of objects such as the giant-planet crossing Centaur population. Calculation of proper orbital elements can reveal groupings of objects, such as collisional families. Identification of objects in mean motion resonances (MMRs) can help test models of the solar system's early dynamical history. The community needs user-friendly, accessible tools for dynamical analyses to fully exploit the upcoming quantity and quality of small body observations and enable transformative scientific progress in many areas of planetary science.

Goals and Objectives: We will develop a well-documented, open-source Python package, Small Body Dynamics Tool (SBDynT) that takes a small body orbit (from observed or modeled populations), performs dynamical integrations of its orbital evolution, calculates a variety of dynamical parameters, and outputs dynamical characterizations and classifications. Example outputs of SBDynT include proper orbital elements, chaos indicators, whether an object is in a planetary mean motion resonance, dynamical classification according to commonly used schemes, dynamical lifetime estimates, and characterization of orbital changes over different timescales, including past orbital history.

Methods and Approach: We will leverage our team's prior experience with dynamical characterization of both simulated and observed small bodies as well as already available open-source tools such as the Rebound orbit integration package to build SBDynT. We will test and validate different approaches for dynamical characterization and classification (e.g., frequency analysis, machine learning) and we will incorporate the ability to characterize an observed small body's orbit using clones to account for observational uncertainties. While generalizable to any small body (observed or modeled), SBDynT will be designed and extensively tested for bodies whose evolution is dominated by gravitational effects (i.e, the main asteroid belt, Trojans, Centaurs, TNOs, etc).

Significance: SBDynT will enable the small body research community to quickly and easily characterize an object based on dynamical behavior; this will be particularly impactful for non-dynamicists who might want to prioritize follow-up observations of objects based on orbital evolution characteristics. For dynamicists, this tool will provide a common platform for both numerical simulations and observed objects, enabling direct and self-consistent comparisons of models to observations. SBDynT will also minimize future duplication of effort by leveraging our expertise to provide a set of dynamical characterization tools to perform common tasks.

Relevance: This proposed effort is relevant to PDART because the goal is to develop and disseminate software tools that facilitate the use of existing datasets or that would enable or enhance future science investigations of interest to the Planetary Science Division". In particular, SBDynT would fulfill the need identified by (Schwamb et al. 2019, arXiv:1802.01783) and (Hsieh et al. 2020, arXiv:1906.11346) to provide dynamical characterization and resonance identification for objects discovered by LSST. It would also enhance the science return of many past and current surveys by providing a consistent dynamical characterization framework for the already existing small body dataset.

Exobiology
Abstracts of Selected Proposals
(NNH21ZDA001N-EXO)

Below are the abstracts of proposals selected for funding for the Exobiology program. Principal Investigator (PI) name, institution, and proposal title are also included. 61 proposals were received in response to this opportunity. On July 20, 2022, 18 proposals were selected for full funding.

Jeanine Ash/William Marsh Rice University
Linking methane biogeochemistry to microbial biosignatures in the Guaymas Basin

Motivation:This proposal is motivated by the need to develop reliable indicators for the origins of methane that may be used on Mars and eventually other solar system bodies, including Enceladus and Titan. Methane forms by a variety of mechanisms, including microbially. Understanding the contributions of biogenic and abiotic processes to the methane cycle is therefore central to ultimately developing methane as a potential biosignature. Earth is the laboratory for honing our understanding of how a new method, rare isotopologues, can be used to determine methane's origins. In the Guaymas Basin, Gulf of California, basaltic sill emplacement in organic-rich sediment provides an opportunity to study the origins of methane in a setting relevant to planetary science. Here, potential sources of microbial, thermogenic and abiotic methane may co-exist, and the resulting subseafloor methane reservoir may in turn be consumed by anaerobic microbial methane oxidizers. International Ocean Discovery Program (IODP) Exp. 385 recently found steeply increasing methane concentrations in deep, hot sediments towards basaltic sills. Integrated methane biogeochemistry and molecular biology can decode how methanogenic microbes, thermogenesis and abiogenesis interact in this extreme subsurface environment.

Objectives:We seek to understand how methane is created and consumed in the Guaymas Basin subsurface by examining methane isotopologue geochemistry in the context of methane-cycling microbes, thermal and abiotic methane-genesis processes. Methane created by axenic cultures in lab experiments has a unique, disequilibrium isotopologue composition, while microbial methane from low-energy environments like the subseafloor tends to have an isotopologue distribution that approaches equilibrium with environmental conditions potentially due to the anaerobic microbial oxidation of methane or slow rates of methanogenesis. Each of these microbial isotopologue signatures are unique compared to both thermogenic methane (equilibrated at gas window temperatures i.e. 150-250°C) and abiotic methane (reflective of high temperatures/kinetic processes). We aim to provide new insights into how abiotic and biological methane production contributes to methane cycling in this dynamic subsurface environment.

Methods:To achieve this, we will use biogeochemical and molecular techniques on samples in hand from two sites: IODP Site U1547 where sill intrusion occurs at ~130 meters below seafloor (mbsf) and U1546, where sill intrusion occurs ~350 mbsf. Thermal gradients at each site cross the threshold of >80°C where thermophilic methanogens may be active, but not methane oxidizers. To determine methane sources and sinks, we will determine the isotopologue composition of subseafloor methane gas and examine adjacent samples for methanogenic and methane-oxidizing archaea by sequencing the key gene, methyl conzyme M Reductase (mcrA) including newly discovered thermophilic mcrA lineages. DNA yield permitting, we will perform metagenomic reconstruction of genomes from methane- and alkane-cycling archaea. Isotopologues (informed by microbiology) will be used to create mixing models to distinguish contributions of microbial methanogenesis, thermogenesis, abiogenesis and oxidation to Guaymas Basin subseafloor methane cycling.

Relevance:This work is relevant to the NASA Astrobiology Strategy and Exobiology because 1) we will determine formation/consumption pathways of methane, a key organic molecule with both microbial and abiotic sources, in extreme hydrothermal subsurface habitats analogous to early-earth or subsurface environments on ocean worlds; 2) we will test the utility of methane isotopologues as biosignatures against microbial sequence indicators, and 3) we will characterize the gene-based phylogenetic and physiological diversity of extant Guaymas Basin methanogens and methanotrophs, whose extremophile characteristics may reflect the nature of primitive environments.

Thomas Boothby/University Of Wyoming
Identifying the Sequence Features and Properties of a Tardigrade Disordered Protein That Promote Multiple Mechanisms of Desiccation Tolerance

Tardigrades are a group of microscopic animals renowned for their ability to survive many environmental extremes including being frozen, heated to high temperatures, being irradiated to orders of magnitude more humans can endure, prolonged exposure to the vacuum of outer space and near complete desiccation (~90-98% water loss). To survive this latter stress, extreme drying, tardigrades use a special family of intrinsically disordered proteins known as Cytoplasmic Abundant Heat Soluble (CAHS) proteins. CAHS proteins serve as 'molecular Swiss Army knives,' capable of preventing multiple forms of stress, such as protein unfolding and protein aggregation, through distinct protective mechanisms. For example, to help prevent protein unfolding during desiccation CAHS proteins help to coordinate the miniscule amount of residual water left in dried tardigrades to form hydration layers around desiccation-sensitive proteins. Conversely, to prevent protein aggregation, CAHS proteins work through a distinct mechanism known as molecular shielding, where their protective proteins get in between aggregation prone-proteins and slow/prevent their association. Despite knowing that CAHS proteins help tardigrades survive extreme drying through distinct mechanisms, what sequence features of CAHS proteins are essential for these different forms of protection are unknown. Here we will uncover what sequence features and properties of

CAHS proteins are essential for their ability to coordinate water and serve as molecular shields, critical mechanisms that allow these proteins to be protective during extreme drying. In addition, since intrinsically disordered proteins are known to be generally more sensitive to their chemical environment than well-folded proteins, and the intracellular environment is known to be highly perturbed during desiccation, we will investigate how chemical changes inherent to drying cells influence the function of CAHS proteins. Understanding how the sequence and chemical environment of a CAHS protein come together to promote multiple protective mechanisms during desiccation will advance our understanding of how organisms cope with changing, often extreme environments. Furthermore, a deeper understanding of how organisms on Earth are able to cope with low or no-water environments will inform our search for new organisms, both here on Earth and elsewhere. Finally, understanding the molecular underpinnings of desiccation tolerance will provide avenues for pursuing biotechnologies, such as the stabilization of sensitive pharmaceutics and the engineering of more hardy crop plants, which will be a benefit to humans both here on Earth as well as during prolonged spaceflight.

Christopher Carr/Georgia Tech Research Corporation
Genome-informed Habitability, Biosignature Potential, and Limit of Methane Production in Planetary Environments

Background: Subsurface environments on Mars and Enceladus are likely presently habitable for life as we know it. Methane measurements by Curiosity and Cassini, respectively, raise the possibility of extant life on these worlds, but at present cannot reliably be distinguished from abiotic sources.

Objectives: Here we propose to leverage both in silico and lab-based experiments to investigate the growth and production of microorganisms in Mars and Enceladus environments. We aim to: 1) Estimate the methanogenic potential of the present subsurface environment of Mars and the ocean on Enceladus, and 2) Determine if microbial methanogenesis can explain the methane observed on Mars and in the plumes of Enceladus.

Methodology: Aim 1a: We will quantify the range of total biomass and biosignatures that could be produced by methanogens given the conditions analyzed by Curiosity and Cassini using genome-scale modeling; we previously used this approach to demonstrate that Gale Lake was once habitable and that detectable levels of biomarkers could have been produced if life was present. Here we expand this work to evaluate habitability based on subsurface conditions and methanogenesis, and predict potential production of a comprehensive set of biosignatures. Aim 1b: We will validate the models with in vitro experimentation of candidate methanogens via long-duration culturing under high-pressure in-situ like conditions. Aim 2a: We will model the range of potential abiotic methane production using a similar framework to aim 1a. Aim 2b: determine if the methane produced in these environments is consistent with abiotic and/or biotic mechanisms by comparing predictions of aim 1a and 2a, and will also identify potential byproducts that could be used in situ to differentiate between abiotic production and extant life.

Relevance: Our work will help to systematically constrain the habitability and biosignature potential of Mars and Enceladus. Of significance, this work would reveal the cell abundance limits sustainable in the subsurface of Mars and Enceladus' ocean, elucidate limits of biosignature production on Mars and Enceladus, and determine if observed CH_4 signals are congruent with a biotic or abiotic source. Our work is responsive to the solicitation themes Biosignatures and Life Elsewhere (primary) and Early Evolution of Life and the Biosphere (secondary). Impacts may include 1) Refining the limits of microbial life; 2) Improving the context of specific biomarkers; 3) Informing future life detection missions and planetary protection.

Mary Droser/University Of California, Riverside
A Welcome Mat for Complex Life: Implications of Diverse and Ubiquitous Ediacaran Organic Surfaces for the Development of Animals and the Recognition of Microbial Structures on other Planets

The Precambrian sedimentary record is characterized by evidence for widespread organic mats. The greatest diversity and complexity of organic mat textures occurs in the Ediacaran, a period that also includes the onset of complex life forms in environments containing ubiquitous mat textures.

Organic matgrounds likely played a pivotal role in the early development and evolution of complex life, potentially providing food and oxygen for mobile and high metabolism taxa. Further, sedimentary features indicative of mats are particularly pervasive and distinctive, demonstrating that the organically-stabilized substrate not only mediated community ecology, but also shaped the sedimentological and stratigraphic expression of Ediacaran successions. As a result, distinct mat signatures preserved on discrete bedding planes and in cross-section, as repeated and readily identifiable sedimentary structures, represent the potential opportunity for image based detection of these biologically important structures via computer visualization programs.

To address these implications of organic surfaces, this research will focus on two fundamental questions:

A) What was the ecological and biological significance of diverse, widespread mats in the advent and success of animal mobility, the distribution of body size and the evolution of complex morphologies?
B) Can we use definitive biotically produced sedimentary structures resulting from widespread mats to develop a quantitative approach to recognize organic surfaces on Earth and other planets?

At Nilpena National Heritage Site, South Australia, 40 excavated beds with both an extensive record of body fossils and organic mat textures as well as sections in the

Flinders Ranges from the Ediacara Member of the Rawnsley Quartzite provide the ideal opportunity to address the two major research questions outlined above through three main objectives:

1) Quantitatively and qualitatively classify the variety and maturity of Ediacaran organic mat surfaces from both the perspective of bedding planes and cross-sectional views.
2) Examine the relationship between these surfaces and the distribution of the Ediacara Biota. In particular, we will test for correlations between mat development and the abundance, variety and size of taxa that may have benefited from increased nutrient or oxygen availability provided by mats.
3) Using cross-sectional views, develop a computer vision program with the ability to recognize bed junction morphologies that are definitively biotic in origin.

Completion of these objectives will first and foremost refine our understanding of organic mat textures, the dominant macroscopic evidence of life on Earth for billions of years, thus directly addressing the NASA ROSES C.5 Exobiology goal to better comprehend the coevolution of microbial communities. Further, we will directly test the role of these mats in the evolution of early animal life contributing to the study of the evolution of advanced life seeks to determine the biological and environmental factors leading to the origin of eukaryotes and the development of multicellularity on Earth". Exploring new techniques for recognizing mat textures and related sedimentary structures beyond our own planet, which represent biosignatures for life and conditions conducive for hosting complex life, will greatly advance our capacity for the recognition (retention) of biosignatures under non-Earth conditions and the potential distribution of complex life in the Universe .

Adam Frank/University Of Rochester
Characterizing Atmospheric Technosignatures (CATS): A Systematic Approach to Non-radio Technosignature Library Development

This proposal seeks to continue and significantly extend our NASA funded work developing a library of spectroscopic signs of extraterrestrial technology (``technosignatures," TS) and to develop the theoretical and modeling framework for populating the library. Our long-term goal is to use this library to develop a comparative framework for evaluating both the strength and non-ambiguity of proposed non-radio technosignatures in exoplanetary spectroscopy. This library will be tuned to NASA missions such as JWST and those selected by the Decadal Survey as they begin to search for signs of life in transmission and, eventually, reflection spectra of exoplanets. We propose 5 specific, linked projects to be carried forward by our team across 3 years.

1. To establish a baseline for TS studies we will carry forward a detailed study of Earth from Earth in which we evaluate the maximum distances for detectability of all viable Earth TS with existing observational capacities.

2. In order to establish a systematic foundation for TS studies of possible trajectories for technological civilizations we will adapt Future Projections methods used in climate science to TS studies. Future Projections is a well-studied method used in climate policy for projecting futures given uncertainties technological capacities. Working with experts in Future Projections we will develop guidelines for its use in TS studies.
3. Using Future Projections as a foundation we will undertake a detailed study of TS resulting from the modification of planetary climates (such as terraforming).
4. Unlike biosignatures, TS do not need to be sited in the same location as the organisms which create them. Space-faring technological civilizations can locate much of their ``industrial" activity on uninhabited or uninhabitable worlds. We will explore a specific example of a TS associated with such ``Service Worlds" in the form of UV reflectance spectra from the large-scale deployment of solar energy harvesting via photovoltaic collectors
5. As with biosignatures, all TS suffer from the possibility of false negatives and false positives. We will develop a formal probabilistic framework for the evaluation of TS false negatives and positives that can be applied to our entire library.

Finally, we note our team comprises a broad collaboration of observers, analytic and computational theorists who are all leaders in the emerging field of technosignatures. We have run a NASA sponsored international meeting and a NEXSS all-day webinar on the field. The work we produce will provide leadership in the field by establishing baselines, methods, and direct characterization of possible technosignatures. Our work will also be shared with the general public through articles written for heavily trafficked platforms such as the NY Times, the Washington Post and others.

Jacob Haqq-Misra/Blue Marble Space
The Life Span of the Biosphere Extended

Models of planetary habitability indicate that the life span of Earth's biosphere is limited. The carbonate-silicate cycle on Earth regulates the atmospheric inventory of carbon dioxide over long time scales as the weathering of silicate rocks draws down volcanically outgassed carbon dioxide. As the sun steadily brightens through its main sequence lifetime, this silicate weathering rate should increase, which thereby causes the atmospheric inventory of carbon dioxide to decrease. Lovelock and Whitfield (1982, Nature) first argued that the trend toward decreasing carbon dioxide in Earth's future would eventually inhibit C3 photosynthesis when atmospheric carbon dioxide falls below 150 parts per million (ppm) in only 100 Myr from now, which would mark the end of the biosphere in general. Caldeira and Kasting (1992, Nature) revisited this problem and argued that C4 photosynthesis remains viable until carbon dioxide levels fall to 10 ppm, which pushes the end of Earth's biosphere to 0.9 to 1.5 Gyr from now. A handful of other studies (e.g., Franck et al. 2000, Tellus; Lenton & von Bloh 2001, GRL; Rushby et al. 2018, Astrobiology) have continued to explore constraints on the life span of Earth's biosphere, some of which consider an extended phase of habitability by extremophiles (e.g., O'Malley-James 2013, 2014; IJA), but all of which rely upon the same 10 ppm carbon dioxide threshold for C4 photosynthesis as a proxy for the end of the biosphere.

This proposal will use climate modeling to demonstrate that Earth can maintain a thriving photosynthetic biosphere below the canonical 10 ppm level of carbon dioxide and can therefore maintain a macroscopic photosynthetic biosphere for much longer than previous estimates. We will perform an analysis based on prior observations and theoretical considerations of C3, C4, and CAM model plants as well as aquatic plants, microalgae, and cyanobacteria to determine the lowest levels of atmospheric carbon dioxide that such populations can sustain. We will use this analysis to develop new biological productivity functions that describe possible and plausible responses of the biosphere to low levels of atmospheric carbon dioxide. We will then apply these new biological productivity functions into an improved modeling framework descendant from Caldeira and Kasting (1992, Nature) to calculate an updated, extended, life span of the biosphere.

This proposal is relevant to the NASA Exobiology program call (C.5) as a theoretical study of "large scale environmental change" that results from feedback between the carbonate-silicate cycle and the evolution of photosynthetic biota. This proposal will identify the extent to which multicellular photosynthetic communities can operate as "planetary processes" that regulate the onset of "rapid climate change" and drive the "large-scale evolution of life on Earth." The proposal will result in an updated calculation of the life span of Earth's biosphere, which will improve constraints on perhaps the greatest "mass extinction event" that will occur in our planet's future.

Tori Hoehler/NASA Ames Research Center
Methanogenic Activity And Isotopic Biosignatures Under Carbon Limitation

Biological autotrophic methanogenesis, a metabolism whereby CO_2 is reduced to methane ($CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$), is an important target in the search for evidence of life elsewhere. Methane has been observed in the atmosphere of Mars and the plumes of ice and gas that originate in the ocean of Enceladus, and biology is among the potential sources in both cases. The design of missions to evaluate the biogenicity of methane on these worlds depends critically on understanding the environmental factors that impact biological and abiotic methanogenesis and the (bio)signatures they leave behind. In the subsurface of both Mars and the Ocean Worlds, much of that context may be provided by the chemistry of serpentinization   a class of water-rock reactions that yields characteristically alkaline, H_2-rich fluids. The mineral reactants and products of serpentinization have been observed in multiple locales on Mars and serpentinization is a likely driver of the alkaline, H_2-rich composition of the ocean of Enceladus.

The chemistry of serpentinizing systems differs dramatically from that of the organic matter-driven systems in which our understanding of methanogen physiology and ecology is almost exclusively rooted. Relative to the high CO_2 and low H_2 concentrations typical of organic-fueled systems, serpentinizing systems become increasingly alkaline as water-rock reaction progresses, and transition from CO_2-replete to CO_2-poor and from H_2-limited to H_2-rich. Each of these factors has the potential to significantly impact methanogenic activity, including the expression of carbon isotope fractionation that can serve as an indicator of biogenicity. To assess these impacts, we propose a systematic, culture-based study with the specific objectives:

1. Quantify rates of methanogen growth and cell-specific methanogenesis as a function of pH, CO2 availability, and H2 availability
2. Quantify carbon stable isotope fractionation during methanogenesis and methanogen biosynthesis as a function of pH, CO2 availability, and H2 availability

We will address these objectives with a comparative study of the autotrophic methanogens Methanococcus maripaludis, an extensively characterized organism isolated from salt marsh sediments, and 'Methanobacterium NSHQ4', an autotrophic methanogen enriched by our group from the Samail Ophiolite, Oman. M. maripaludis exemplifies our current understanding of methanogen physiology, which derives almost exclusively from organisms isolated from CO2-replete environments and characterized under CO2-replete conditions. In contrast, M. NSHQ4 is one of only two methanogens thus far cultured from hyperalkaline, CO2-poor, and H2-rich fluids in a serpentinizing environment. While M. NSHQ4 and related taxa are notably abundant in serpentinizing systems, their presence there is not explained by our current understanding of methanogen physiology and their activity has not been characterized under relevant environmental conditions. Our study will employ chemostat culturing to quantify isotope fractionation and key physiological parameters (maximum growth rate, growth yield, and substrate half-saturation constants) under prescribed and stable experimental conditions, and batch culturing to quantify activity and C isotope fractionation across a broad matrix of pH, CO2, and H2 that pushes toward the most extreme conditions in which evidence of methanogens is seen in terrestrial serpentinizing systems. The results of this study will provide a basis on which to build a predictive understanding of the habitability and biosignature potential of serpentinizing systems with respect to methanogenesis.
The proposed work is directly relevant to the Biosignatures and Life Elsewhere" element of the Exobiology Program through its focus on methanogen activity and carbon isotope dynamics in serpentinizing systems, which may be prevalent in subsurface settings beyond Earth.

Julie Huber/Woods Hole Oceanographic Institution
Targeted Life Detection of Marine Alkaliphilic Methanogens in Subseafloor Fluids from Serpentinite Mud Volcanoes of the Mariana Forearc

The hydration and alteration of ultramafic rocks in Earth's oceanic crust is called serpentinization. This process is thought to extend far into Earth's history, potentially playing a role in the origins and early evolution of life. There is also evidence that serpentinization has occurred on Mars and ongoing serpentinization may explain geochemical signatures from the ocean plumes of Saturn's moon Enceladus. In the high pH, reducing conditions that result from serpentinization, the abiotic reduction of inorganic carbon to various organic compounds is also occurring. The products of both this process and serpentinization are primary energy sources for non-photosynthetic, autotrophic life on Earth, especially methanogenic and anaerobic methane oxidizing archaea. However, the reducing environments in which these processes occur also present challenges to microbial life with respect to the extreme pH (>10) conditions and often a lack of nutrients or electron acceptors. The recent discovery of extremely high pH (12.5) fluids associated with serpentinite mud volcanoes along the Mariana forearc in the western Pacific provides an opportunity to directly examine the limits of microbial methane cycling archaea at the extremes of high pH and across a gradient of pressure, hydrogen, carbon, and temperature.

The overall goal of this research is to determine the presence and activity of anaerobic microbial methane cycling at the polyextremes of high pH and high pressure in newly-collected cool, alkaline subseafloor fluids of the serpentinite mud volcanoes of the Mariana Forearc. Given we will potentially be working at extremely low cell concentrations, we include various techniques for analyzing methanogenic and anaerobic methane oxidizing microbes in the fluids, including NanoSIMS, stable isotope geochemistry, microbial enrichments, cell quantification, microscopy, and genomic analysis. To date, no cultured marine alkaliphilic methanogens exist, and their identity and activity at such extremes is unknown. We will examine the activity, physiology, and genomic features of anaerobic subseafloor methane cycling microbial community members using newly collected samples from subseafloor fluids of serpentinite mud volcanoes. Our biological data will be collected in the context of a rich geochemical dataset spanning inorganic, organic, and dissolved gas chemistry provided by our NSF-funded collaborators.

This work addresses multiple NASA Exobiology research areas, including the investigation of "Biosignatures and Life Elsewhere," and specifically "basic research on the formation and retention of biosignatures under non-Earth conditions (e.g., Mars, Europa)." The results of this work will inform the detection of microbial life in high pH, high pressure saline habitats and thereby inform life detection in similar environments, such as the Enceladus ocean, aligning with the NASA Exobiology goal of studying samples from Earth sites thought to be analogues of other planetary environments that might potentially harbor life." In addition, this work addresses the Early Evolution of Life and the Biosphere research area by examining the phylogeny and physiology of microorganisms, including extremophiles" and studying the coevolution of microbial communities, and the interactions within such communities, that drive major geochemical cycles."

Together, our work will provide a comprehensive picture of habitability for marine alkaliphilic methane cycling microbes in the highest known pH setting in the ocean on Earth. Given serpentinization is likely a universal process across the solar system, our work identifying and quantifying the activity of marine alkaliphilic methane cycling microbes and their energetic and functional adaptations to this harsh environment will help constrain not only the limits to life on Earth, but also what life could exist beyond Earth.

Christopher Jeffrey/University Of Nevada, Reno
UV-C Screening in Cyanobacteria: Exploring the Photophysics and Chemistry of Photo-Thermalization by the Pigment Polysaccharide Sheath.

Cyanobacteria are extremophiles that establish the conditions for life in a world depleted of oxygen and the ozone that filters lethal UVC light. These organisms existed approximately 2.4 billion years ago, predating the oxygen rich conditions that supports the biota of present day. It has recently been established that cyanobacteria found in deserts with the most extreme environmental conditions on our planet can withstand extended exposure to UV-C radiation, mimicking the levels of early Earth and on the surface of Mars. The overarching question of this study is: what are the molecular characteristics of the extracellular cyanobacterial sheath that provide the efficient resistance to UV-C radiation?

Scytonemin is a broad-spectrum UV absorbing pigment that is dispersed in the characteristic polysaccharide extracellular sheath of cyanobacteria. This co-occurring pigment-polysaccharide trait has been conserved throughout many cyanobacteria taxa over the billions of years of evolutionary history. Studies have shown that scytonemin can act specifically to absorb UV-C light and as an efficient free-radical scavenger; however, these properties do not parallel the thermalization conditions that must be met for prolonged UV-C exposure. We hypothesize that the non-covalent interactions of the pigment within the polysaccharide matrix provide the unique capability to absorb this and efficiently thermalize this radiation without causing lethal damage to the organism. The objectives of this proposal focus on exploring the photophysics and chemistry of the photon thermalization process of the pigment- polysaccharide matrix. We seek to characterize and understand the role of the polysaccharide-pigment interaction in the efficiency of photon thermalization using a multi-disciplinary team of scientists and use methods steady state UV-Vis spectroscopy, ultra-fast laser spectroscopy, computational chemistry and natural products chemistry. The two main objectives of this proposal are: (1) Evaluate the effect of the polysaccharide-pigment interaction on the photostability and photophysical properties of scytonemin and (2) Elucidate and compare the mechanisms of energy transfer in the scytonemin polysaccharide sheath.

Approach and methods: The two main objectives of this proposal will be achieved through the completion of 4 tasks: Evaluate and compare the photostability of scytonemin when unsheathed vs. sheathed in a polysaccharide film, (2) compare the transient ground state absorption lifetimes and transitions of scytonemin when unsheathed vs. sheathed in a polysaccharide film, (3) elucidate and compare mechanisms of energy transfer unsheathed vs. sheathed pigments using ultrafast 2D-white light spectroscopic data, and (4) elucidate and compare the mechanisms of energy transfer unsheathed vs. sheathed pigments using computational data.

Significance to NASA programs: The objectives of this proposal directly overlap with the goals of the NASA's exobiology program by focusing on understanding key aspects of the origin, distribution, and future of life in the Universe. An understanding the physiology of these extremophilic UV-C resistant cyanobacteria directly target topics within early evolution of life and the biosphere research area of the exobiology program.

Gerald Joyce/Salk Institute for Biological Studies, San Diego, California
Evolution of Catalytic RNA and the Origins of Life

The proposed research pertains to a simple form of RNA-based life that likely existed during Earth's early history as a predecessor to contemporary DNA- and protein-based life. Building on progress made over the past grant period, the central aim of the proposed research is to construct RNA-based life in the laboratory, as represented by populations of RNA polymerase ribozymes that catalyze their own replication and undergo Darwinian evolution in a self-sustained and open-ended manner. If the self-sustained replication and evolution of RNA can be achieved in the laboratory, then the RNA world can be studied experimentally, enabling direct investigation of a key stage in the origin of life that has been lost to natural history.

During the prior years of this research effort, directed evolution was used to optimize the activity of the class I polymerase ribozyme. Over the course of 52 successive generations" of evolution, the ribozyme underwent a dramatic structural rearrangement of its catalytic core. As a result, the polymerase now has substrate recognition properties and other catalytic features comparable to those of polymerase proteins, with the ability to synthesize functional RNAs up to 100 nucleotides in length and to replicate small RNAs by 10,000-fold. The currently most advanced polymerase ribozyme, which contains ~200 nucleotides, is not yet able to synthesize and amplify itself, but that goal now appears to be achievable with further optimization.

Directed evolution will be used to obtain a polymerase ribozyme that can synthesize functional copies of its ancestor, the class I RNA ligase, and, as activity improves, to synthesize copies of itself. Over the course of evolution, three attributes will be targeted that are essential for an RNA replicase: i) rapid and sequence-general copying of RNA templates; ii) improved fidelity of polymerization; and iii) displacement of the complementary RNA strand during synthesis. The current form of the polymerase has advantageous properties with regard to each of these attributes, suggesting that further evolutionary optimization will be possible.

The polymerase ribozyme will also be evolved to catalyze the exponential amplification of functional RNA molecules. A microfluidic-based system has been developed to evolve polymerase ribozymes within individual droplets of a water-in-oil emulsion, which correspond to the compartmented environment of a biological cell. Polymerase ribozymes will be seeded across billions of droplets and selected for their ability to amplify other RNA molecules. The fitness of the evolving RNAs will be based on how they affect the properties of the compartment in a manner that contributes favorably to replication of those RNAs. Ultimately, the polymerase will be made to replicate itself, evolving towards fully autonomous replication.

The transition from RNA- to DNA-based life would have required the transfer of genetic information from RNA to DNA. It was recently shown that the most advanced RNA polymerase ribozymes can also catalyze the reverse transcription of RNA to DNA and the forward transcription of DNA to RNA. Directed evolution was used to improve both these activities. Further evolution will now be carried out to enhance DNA polymerase activity, selecting for the ability to synthesize functional DNA molecules. These efforts will demonstrate the potential for RNA-based life to invent DNA genomes prior to the emergence of instructed protein synthesis.

Finally, with a system for self-sustained RNA evolution in place, it will be possible to conduct open-ended evolution experiments, providing both a working model of RNA-based life and a testbed to address how RNA-based life could have evolved more complex functions. An RNA-based system that is able to generate copies of itself would be self-optimizing and would provide the first example of a living system outside of terrestrial biology.

Kimberly Lau/Pennsylvania State University
Experimental constraints on dolomite geochemistry as an archive of seawater redox evolution

The motivation of this proposal is to provide currently missing fundamental constraints on the efficacy of dolomite as a paleoredox proxy archive specifically, U and S and their isotope ratios. The already extensive dolomite-hosted paleoredox proxy records (including U and S) constrain paleoredox evolution and environmental change across the major biospheric evolutionary events through the Precambrian, when dolomite was ubiquitous. Simultaneous to these widespread applications, there is significant debate as to the integrity of carbonate paleoredox constraints given the potential for late-stage diagenetic alteration in highly evolved pore fluids. In this case, dolomite geochemistry and stratigraphic variability reflects pore fluid chemistry and changes in carbonate preservation (e.g., diagenesis or the lack thereof). Yet in the Precambrian, there is geochemical and textural evidence that dolomitization may have occurred syndepositionally or during early diagenesis in exchange with seawater (i.e., early 'fluid-buffered' dolomite) and thus having the potential to preserve seawater geochemical signatures. Therefore, constraints on trace element incorporation into dolomite are necessary and timely for dually advancing quantitative paleoredox proxy applications and recognizing temporal trends in 'early' vs. 'late' dolomite mineralization (i.e., the dolomite problem).

We propose two complementary experimental approaches to investigate trace element incorporation into dolomite under well-controlled laboratory settings: replacement dolomitization and seeded dolomite precipitation. Via high-temperature dolomitization experiments, our proposed work will provide important geochemical constraints coefficients, isotope fractionation factors, and speciation for S and U isotope paleoredox proxies necessary for mass balance and diagenetic models that quantitatively link dolomite geochemical proxies and seawater chemistry. Our proposed work is motivated by our recent success with analogous dolomitization experiments for proxy calibration for I/(Ca+Mg) into diagenetic dolomite minerals. By combining the unique information to be gleaned from each approach we will:

1. Determine partition coefficients for S and U in dolomite.
2. Determine isotope fractionation factors (alpha) for ´34S and ´238U between source fluid and dolomite.
3. Determine the effect of redox speciation on U in dolomite.

The U and S proxies are chosen because of their extensive existing ancient records, distinct sensitivity to redox conditions, existing developed mass balance models for quantifying global redox states, and field-based and preliminary diagenetic modeling evidence indicating their potential for quantitative ancient applications. Ultimately, the expected outcome of this project is to develop guidelines for recognizing 'early' dolomite and the conditions that best preserve seawater ´34S and ´238U via models that are (1) parameterized with the constraints that will be obtained in this study and (2) calibrated against data from recent dolomites formed under variable conditions. We expect that our work will provide a blueprint that can be applied to other, already commonly used, carbonate redox proxies in dolomite.

Relevance: Fundamental questions in Earth History regarding when oxygenic photosynthesis evolved, the dynamics of atmosphere-ocean oxygenation, the dependence (if any) between early eukaryotic evolution and oxygen availability, and the relationship between anoxia and mass extinctions are aligned with the scopes of several research emphases in NASA Exobiology. Toward this end, NASA has invested heavily in the growing published record of carbonate-bound paleoredox proxies. However, an interpretative framework that takes into account the effects of carbonate mineralogy and early marine diagenesis for these proxies (with U and S at the forefront), and particularly for dolomites, remains unrealized, limiting interpretations.

Xiaolei Liu/University Of Oklahoma, Norman
Novel thioxo-arsenolipids for arsenic biogeochemistry: a study of molecular structures, isotopes, and natural distributions to understand their biological sources and biogeochemical significance

Arsenic is a toxic metalloid that ubiquitously occurs in present-day environments and has been proposed by recent works to be more abundant in the primordial ocean. The capacity for metabolizing arsenic by diverse microorganisms is believed to have evolved early in the evolution of life but become more prevalent as marine phosphate levels decreased given the chemical similarity of phosphate and arsenate. However, the study of arsenic biogeochemistry in deep time is hindered by the paucity of microbial fossil records. Facilitated by a novel analytical application in a pilot study we have detected a suite of thioxo-arsenolipids that are widespread in various depositional environments ranging from modern water column to over 100 Ma old black shale. These arsenic bearing compounds are not diagenetic products, but biological molecules synthesized by yet unrecognized anaerobic microbes metabolizing arsenic, and therefore represent a set of novel biomarkers for arsenic biogeochemistry.

With this proposed work we will establish the LC-qTOF-MS method for arsenolipid analysis (Objective 1). Targeted thioxo-arsenolipids will be isolated using prep-LC and their structures will be determined by mass and NMR spectroscopy (Objective 2). We will characterize the distributions and potentially isotopes of these thioxo-arsenolipids through a study of the meromictic Fayetteville Green Lake water column. Metagenomic and metatranscriptomic data of the planktonic microbial communities at different depths of Green Lake water will reveal the distributions of targeted arsenic resisting genes and corresponding microbial species (Objective 3). All results, including molecular structures, lipid distribution in Green Lake water, isotopes and metagenomics, will help constrain or potentially identify the thioxo-arsenolipid producing microorganisms. Furthermore, we will explore the preservation of the thioxo-arsenolipids and their degradation derivatives in various geological samples of different ages (Objective 4). The proposed experiments, if successful, will establish a thioxo-arsenolipids based molecular proxy for studying arsenic biogeochemistry, which could be coupled to both sulfur and carbon cycles, in present environment and geological past.

The proposed work is relevant to the Exobiology theme of Early Evolution of Life and the Biosphere because it is concerned with evolution of arsenic biochemistry as well as the coevolution of microbial communities involved in arsenic, sulfur, and carbon cycles. For the theme of Large Scale Environmental Change and Macro-Evolution the research will expose the impact of extreme geochemical conditions (high arsenic, low phosphate concentrations) and long-term environmental change to the microbial life in ancient ocean. The research is also relevant to the theme of Biosignatures and Life Elsewhere as it relates to the potentially alternative biochemistry, arsenolipids vs. phospholipids, for the origin and establishment of life under conditions prevailing on other planetary bodies.

Andrew Mattioda/NASA Ames Research Center
Looking for a Biotic Needle in a Kerogen Haystack

The proposed research will elucidate biomarker diagenesis under surface radiation conditions on Ocean Words, such as Europa and Enceladus. This will be accomplished by characterizing the changes in chemical composition and molecular structure that organic biosignatures (e.g., lipids) undergo during electron irradiation at low temperatures (15 K) and vacuum conditions. We will differentiate between the direct effects of radiation on organic molecules, and the indirect effects caused by the radiolytic products of water-ice (free radicals and reactive oxygen species or ROS). This will be accomplished by irradiating the samples in the presence and absence of H2O ice, with the bare sample (absence of ice) providing the changes induced by radiation alone. Similarly, radical species produced by irradiation of organics in water ice at 20 K will be characterized via in situ Raman and IR spectroscopy while any volatile species given off will be detected via mass spectroscopy (MS). Samples will then be heated, mimicking the sample handling steps by in situ planetary instruments such as the Europa Lander's, providing a contrast between the ROS changes to irradiation changes of the bare samples and low temperature ices (i.e., generation of radical species). Post-irradiation residues (structurally similar to kerogens) will be further analyzed via Gas Chromatography Mass Spectrometry (GCMS) to determine the molecular structures of the breakdown products These experiments will be conducted on biotic (i.e., lipids) molecules as well as an abiotic one (i.e, a PAH - commonly found in organic material throughout the Solar System), permitting us to identify differences and similarities in the degradation patterns. The biotic samples will be ran as single molecules as well as mixtures of molecules, permitting us to identify how increasing molecular complexity influences the end results. These comparison will permit us to identify the radiation dose at which the degradation products of both the biotic and abiotic become a kerogen like material, indistinguishable from each other.

The Raman, IR, MS and GCMS data generated by this proposed work will be uploaded to existing, online, searchable databases providing a legacy value for future NASA missions as well as the scientific field in general.

Jill Mikucki/University Of Tennessee, Knoxville
Of ice and brine: Persistence strategies in a chaotropic, Antarctic exobiological analogue

Life as we know it requires a liquid milieu. Given the extreme cold temperatures on Mars and Ocean Worlds, any liquids there are likely to be rich in solutes, including chaotropic salts. Such brines present distinct challenges for survival and metabolism of microbial life as we know it. On Earth, extremophilic life has adapted to a range of salty conditions and can potentially tolerate water activities (aw) as low as 0.61. Cellular survival in hypersaline conditions is well studied, with extreme halophiles tolerating saturated NaCl solutions (aw as low as 0.75). However, less is known about brines high in chaotropes, such as Ca2+ and Mg2+. Chaotropic conditions can destabilize membranes, degrade most cellular components and inhibit metabolism, making persistence in chaotropic brines a distinct challenge to life. Don Juan Pond (DJP) is a hypersaline pond (up to 400 g/L) in the McMurdo Dry Valleys, Antarctica that is saturated with calcium chloride (~95%), resulting in extremely low aw (H 0.45). The presence of microbial life in this system has eluded scientists by many metrics and it is thought that the high Ca2+ and low water activity create a chaotropic setting, potentially prohibiting life, and decimating biosignatures.

This proposal will examine materials collected from Don Juan Pond, a Mars analogue site in the McMurdo Dry Valleys, Antarctica, in order to investigate mechanisms that enable microbial survival in a seemingly inhospitable saturated CaCl2-brine. To achieve this goal, we propose an interdisciplinary study to examine the molecular underpinnings, phenotypic manifestations, and mineral characteristics of microbial persistence in an analogue, chaotropic brine by addressing the following research tasks:

1) Determine the genetic links to persistence using enrichment cultivation and metagenomics,
2) Investigate biofilm formation as a mechanism enabling microbial persistence and activity,
3) Analyze spatial associations and preservation of microbial cells and minerals, and
4) Integrate and validate findings from Tasks 1-3 with a reductionist approach, testing the persistence of a defined microbial community in chaotropic brines.

This work will directly address specific 'unknowns' regarding the saline limits for life including how microorganisms retain viability and metabolic activity in situ in liquids with water activity (below 0.61 aw). Our approach will also examine the effect of a biophysically complex brine on the survival, activity and morphology of microbial communities. Studies on the persistence, metabolic activity, and phenotypic changes associated with microbial cells inhabiting natural chaotropic settings are necessary to better understand transient niches where life might be found on Mars or within the ice cover of Ocean Worlds. This proposal is relevant to the Exobiology Program stated goals including to understand the phylogeny and physiology of microorganisms, including extremophiles, whose characteristics may reflect the nature of primitive environments and investigate the evolution of genes, pathways, and microbial species subject to long-term environmental change relevant to the origin of life on Earth and the search for life elsewhere."

Ulrich Muller/University Of California, San Diego
Prebiotically Plausible Oligomers as Ribozyme Cofactors

The proposed work will address how proto-peptides and RNAs could have interacted during the first stages in the emergence of life. While prebiotic model reactions and analyses of meteorites show that short proto-peptides likely existed on prebiotic Earth, the nature of biology's machinery to synthesize proteins suggests that catalytic RNAs existed before encoded polypeptides existed. Therefore, short proto-peptides and catalytic RNAs likely co-existed. The proposed work will address the question whether, and how proto-peptides could have aided in the emergence, and function of catalytic RNAs.

The proposed work will be based on classical techniques in RNA biochemistry, an iterative high-throughput screen analyzed by high throughput sequencing, and an in vitro selection experiment from about 100 trillion sequences, which is also analyzed by high throughput sequencing. This combination of established techniques studying individual types of RNAs and peptides, as well as combinatorial techniques studying large numbers of RNAs and peptides, will enable the identification of novel RNA catalysts that utilize peptide cofactors, the classification of existing RNA catalysts from ~100 previously developed RNA catalysts, as well as the characterization of individual RNA/peptide pairs that serve as model systems to test specific hypotheses on the mechanism.

The results of the proposed work will be significant to the objectives of the solicitation, and the objectives of NASA because they will show pathways in 'prebiotic evolution' that could have been taken by early life forms, and therefore identify what chemical systems could have served as precursors of metabolic and replicating systems on Earth and elsewhere.

Chadlin Ostrander/Woods Hole Oceanographic Institution
Elucidating Marine Redox Conditions Across the GOE using TI and V Isotopes

To assess the potential for Earth-like exoplanets to host life, we must first understand the process by which Earth itself became habitable. For Earth, one important step in its path to becoming a habitable planet was the initial accumulation of molecular oxygen (O2) at its surface   the so-called Great Oxidation Event", or GOE" for short (~2.5 to 2.2 billion years ago). Unfortunately, most of what has been learned about Earth's GOE over the past two decades centers on the atmosphere; comparatively little has been learned about the effects of the GOE on Earth's oceans. This fact becomes especially unfortunate if Earth's oceans were an important location for the origin and evolution of life   an idea that is generally accepted by the early-Earth scientific community.

Herein, we propose to constrain the oxygenation history of Earth's oceans across the GOE by measuring thallium (Tl) and vanadium (V) isotope ratios in shales deposited between ~2.6 and ~1.8 billion years ago. Each of these isotope systems is proven capable of independently tracking ocean redox conditions on a beyond-local scale in Earth's past (i.e., regional if not global). Thallium isotopes are directly sensitive to manganese oxide burial, and therefore indirectly sensitive to O2-bearing (oxic") bottom waters. Vanadium isotopes, on the other hand, respond most strongly to H2S-bearing (euxinic") bottom waters. All of our targeted shale units are well-characterized, having been the target of various previous geochemical investigations. Most importantly for our purposes, atmospheric O2 conditions during deposition of each unit are independently constrained (most commonly, through the measurement of mass-independent sulfur isotope anomalies in the same samples). Our penultimate goal is to compare and contrast ocean and atmospheric redox conditions across Earth's GOE. How did ocean redox conditions evolve across Earth's GOE, and to what extent were these conditions linked to atmospheric redox? In answering these questions, we will better understand the process of Earth's oxygenation   a process that very well may have unfolded on other worlds beyond our own.

Matthew Pasek/University Of South Florida, Tampa
In Search of Prebiotic Phosphorylating Agents that can Provide Continuity with Transition to Biological Processes: Nitrogenous and Reduced Phosphorus Compounds.

The proposed work seeks to understand the emergence of alternative abiotic organo-phosphorylation chemistries and reactions that harbor the potential to transition naturally to the forerunners of nascent biochemical pathways leading to biomolecules (such as nucleic acids). It does so by coupling two recent findings: that energetic phosphorus compounds such as phosphides and those with PH bonds are produced in the environment through several reductive processes, and that energetic phosphorus compounds with PN bonds are excellent phosphorylating agents. However, the PH compounds are poor phosphorylating agents, and the PN compounds are not known to occur naturally outside of biology where they are metabolic transitional molecules. Therefore, we propose to investigate the phosphorylation potential and natural sources of both PH and PN compounds, as well as how natural transformations of PH into PN compounds can be effected. In doing so, the work will help address the long-standing problem of how phosphorylated biomolecules including polymers such as DNA and RNA can arise through natural processes of transitioning from abiotic chemistry to biology.

The proposed work will be accomplished primarily through experimental work such as investigating the reactivity of various PN and PH compounds towards organics such as nucleosides, determining the geologic sources of PN and PH compounds by analyzing natural samples, and searching for plausible routes of PH to PN transformation using mineral-based experiments and simulated prebiotic environments . Equipment needed includes furnaces and a laser, which are available to our labs. Most samples generated in these experiments will be investigated by 31-P NMR, a tool we have used extensively in our prior research, in addition to MS, H and 15-N NMR, Raman, XRD, and other tools available in the Krishnamurthy and Pasek labs. In addition, some amount of modeling will be done, mainly to investigate the thermodynamic stability of PN and PH species, and to investigate the predominant phases expected across a range of plausible environments. This will be accomplished using a commercial software, HSC Chemistry, which the Pasek lab has used in prior work.

If the proposed work is successful, then a route from energetic phosphorus compounds that occur naturally phosphides and phosphites will be shown to provide PN compounds that are superior phosphorylating reagents for the formation of biomolecules. Given the central role of phosphorus in the molecules of life (RNA and DNA, especially), an identification of a coordinated geochemical to prebiotic to biotic chemistry transition could have a major impact in our understanding of how prebiotic molecules arise spontaneously from the environment. As such, the work is directly relevant to Exobiology, and has the potential to explore the question of Are we alone in the Universe?" If these chemical systems arise from natural geochemical environments, then life like our own (nucleic acid-based) may be more plausible beyond the earth and could suggest a fecund universe.

Solar System Observations
Abstracts of Selected Proposals
(NNH21ZDA001N)

Below are the abstracts of proposals selected for funding for the Solar System Observations program. Principal Investigator (PI) name, institution, and proposal title are also included. 19 proposals were received in response to this opportunity. On June 8, 2022, 8 proposals were selected for funding.

Alexander Akins/Jet Propulsion Laboratory
Exploration of the Deep Atmosphere and Surface of Venus at Radio Wavelengths

We propose a campaign of microwave continuum observations of Venus to study global thermal structure in the troposphere and near-surface compositional properties in complement to recently selected NASA Discovery missions and the NASA VenSAR contribution to EnVision. Our proposed observations of Venus' thermal structure with the VLA and ALMA will assess the thermal lapse rate with 10 km vertical resolution and search for horizontal wave features with weak thermal amplitudes. The vertical distribution of atmospheric lapse rates and presence/lack of horizontal waves will be used to distinguish between wave-based and convective angular momentum transport mechanisms in the maintenance of mesospheric super-rotation. Our proposed observations of Venus' surface with the VLA and GMRT will assess the extent to which Venus' anomalous low sub-surface emissivity is global or regional in extent. Confirmation of shallow sub-surface compositional heterogeneity with global extent would have important implications for our understanding of Venus' resurfacing history and surface-atmosphere weathering. We will use layered atmospheric and surface radiative transfer codes to interpret these ground-based interferometer observations and assess instrumental and systematic uncertainties on our results. This proposal takes advantage of recent upgrades to powerful radio observatories to investigate long standing questions about Venus lower atmosphere and near surface properties. Our proposal is relevant to priority VEXAG and Decadal Survey science questions for Venus study and comparative study of terrestrial planets.

Richard Cartwright/SETI Institute
Unraveling the origin and nature of non-ice species on the icy Galilean moons

Background and Motivation:
Europa, Ganymede, and Callisto are ocean worlds with surface compositions that have been modified by interior-surface geologic communication, charged particle bombardment, and dust mantling. On Europa and Ganymede, salts might have originated in their subsurface oceans and have been exposed in geologically young provinces. On

Callisto, organics and/or sulfur-rich volatiles may have been delivered in dust grains that originated on Jupiter's irregular satellites. Furthermore, surface constituents on the icy Galilean moons are continually bombarded by charged particles trapped in Jupiter's magnetosphere, which generate new radiolytic products from salts and the other non-ice species on their surfaces.

Non-ice species on the Galilean moons exhibit numerous diagnostic absorption features over longer near-infrared wavelengths (long-NIR", 3 - 5 microns), which are hinted at in spectra collected by the Near Infrared Mapping Spectrometer (NIMS) on the Galileo spacecraft and the Jupiter Infrared Auroral Mapper (JIRAM) on the Juno spacecraft. However, NIMS' low resolving power, numerous filter junctions, and the low signal-to-noise (S/N) of NIMS spectra at wavelengths > 4.2 microns has limited analyses of these non-ice absorption features using NIMS data. Although JIRAM has collected higher quality spectra of Europa and Ganymede, there are no existing or planned JIRAM observations of Callisto, JIRAM has a filter gap between 3.76 and 3.85 microns, and the S/N of JIRAM spectra is much lower at wavelengths > 4 microns. Consequently, the nature and origin of non-ice species remain poorly understood because of the low quality of existing long-NIR datasets.

Objectives:
1. Determine the spectral signature and spatial distribution of salts that may have originated in subsurface oceans on Europa and Ganymede.
2. Determine the spectral signature and spatial distribution of radiolytic products on the icy Galilean moons.
3. Determine the spectral signature and spatial distribution of organics and/or S-bearing species that may have been delivered in dust grains to Callisto.

Methodology:
Task 1: Collect longitudinally resolved, long-NIR spectra with IRTF/SpeX over the leading, anti-Jupiter, trailing, and sub-Jupiter quadrants of each moon.
Task 2: Collect spatially resolved long-NIR spectra with Keck AO/NIRSPEC over geologically younger terrains on Europa and Ganymede, and the Valhalla and Asgard impact basins on Callisto.
Task 3: Measure detected absorption features and quantify their spatial distributions.
Task 4: Compare all detected absorption features to laboratory spectra of salts and other non-ice species.

Relevance to NASA & SSO Goals:
The proposed work would provide new knowledge on the habitability of subsurface saltwater oceans in the icy Galilean moons. Investigating the habitability of ocean worlds is highly relevant to NASA's goals, as stated in the 2020 NASA Science Plan. The proposed work is also highly relevant to the SSO21 call, which states (C-6.1): "New observations that enhance, complement, or otherwise expand on the science of NASA missions are especially encouraged." Our proposed observations would complement ongoing observations by Juno's JIRAM spectrometer, which has a filter function between 3.75 to 3.86 microns that completely obscures spectral features in this wavelength range

and partly obscures nearby spectral features (between 3.7 and 3.9 microns). Our proposed observations would fill this wavelength gap, providing key information on salts and other non-ice species. Our proposed observations would also complement upcoming observations by NASA's James Webb Space Telescope with the NIRSpec spectrograph, by filling an unrecoverable wavelength gap that shifts between 3.99 to 4.2 microns. Furthermore, our proposed ground-based observations would help refine the spectroscopic objectives of the upcoming NASA Clipper and ESA JUICE missions to the Jupiter system.

Anita Cochran/University Of Texas, Austin
Comets: Clues to Conditions in the Early Solar Nebula

The proposed work will collect new high spectral resolution optical spectra of comets using the 2.7m Harlan J. Smith Telescope of McDonald Observatory and the Tull Coude spectrograph. We include a list of seven comets of various dynamical types that we know will be appropriate targets for our investigations and that are available to observe in the execution period of the grant. In addition, we will add to our list any newly discovered comets that are bright enough for our observations. With these observations, we seek to collect data that are relevant to use to constrain models of the early solar nebula (though such models are not part of this proposal). Our observations are targeted to answer some fundamental questions:
1) What is the relationship between the primordial nucleus of a comet and what is observed in the coma today and how is this influenced by photochemistry?
2) What properties of comets are the result of evolution vs. formation and how have chemical processes influenced comets?

The spectra that we collect will be used: 1) to study the photolysis of C2, 2) to determine the isotopes of carbon and nitrogen in comets, 3) to determine the quantity of CO2 in the coma using forbidden oxygen transitions as a proxy for directly observing CO2, and 4) to earch for how cometary activity differs within 1AU of the Sun. We will use IR observations of the same comets observed at similar epochs and collected by Collaborator Dello Russo to constrain the parent (primary) species that relate to the daughter (photodissociation products) we observe in the optical. We are extremely experienced with these types of observations and analyses.

The observations and analyses that we outline in this proposal are responsive to the NRA ``Research Opportunities in Space and Earth Sciences (ROSES) 2021" for the Solar System Observations Program. They will enable us to obtain new observations to "understand the physical, chemical ... processes that shape the ... exospheres ... of solar system objects"

Neil Dello Russo/Johns Hopkins University
Disentangling natal and post-formation processing in comets through high-resolution infrared observations

We propose high-resolution near-infrared (IR) spectroscopic observations of comets to analyze emission from parent species (i.e., originally stored as ices in comet nuclei) including symmetric hydrocarbons (C2H6, C2H2, CH4), oxidized carbon compounds (OCS, CH3OH, H2CO, CO), nitrogen species (NH3, HCN), and H2O. These proposed measurements are of fundamental importance for understanding the molecular inventory and the sources of volatile release in comet nuclei, which are primitive (through not pristine) remnants from the early solar system. Integrating findings on composition and outgassing sources has become especially relevant in the post-Rosetta era of cometary science. As such, our observational program is also designed to test the degree to which formation conditions and evolutionary processing affect the current chemistry of comets. The three-year period of this proposal offers the opportunity to study comets with a range of dynamical histories. This includes two Oort cloud comets (OCCs) one with a long-period and one Halley-family comet (HFC) in a more evolved shorter-period orbit and several dynamically-evolved Jupiter-family comets (JFCs). We will also observe any newly discovered comet or target of opportunity that is available and sufficiently bright for our proposed science; we expect 1 - 2 such comets per year based on recent discovery rates. We primarily utilize two complementary ground-based facilities highly appropriate for this study: NASA's InfraRed Telescope Facility (IRTF) and the W. M. Keck Observatory.

There are four proposed tasks for this work linked to critical needs in the post-Rosetta field of cometary science. (1) Pursue multi-apparition studies as a new frontier in understanding the volatile chemistry of comets. Such studies provide fundamental insights and evidence for the thermo-chemical evolution (or lack thereof) in short-period comets. (2) Conduct the first observations of parent volatiles in several JFCs and a HFC to investigate (A) underrepresented dynamical classes in compositional studies of parent species, and (B) prospective spacecraft targets for NASA missions. (3) Test current hypotheses for compositional trends within the comet population, emphasizing measurements of parent volatiles that are underrepresented in previous studies. (4) Prioritize measurements of key indicators of volatile ice sources and associations in comet nuclei through detailed study of the spatial distributions of volatiles in comet comae. This work will be pursued in synergy with mm/sub-mm and optical observations, complementing the unique strengths of each wavelength domain.
This work is relevant to NASA's SSO Program because we plan new ground-based comet observations as defined in the scope of the program. Ground-based studies are required for understanding comets as a chemically and dynamically diverse population because only a few comets will be visited by spacecraft. Furthermore, our proposed studies of JFCs will improve understanding of their composition and outgassing sources, thereby helping to put previous mission targets (e.g., 103P/Hartley 2) into the context of the larger ground-based IR compositional database and to evaluate other comets as prospective future NASA mission targets.

Matthew Knight/University of Maryland
Modernizing Our Understanding of the Activity of Oort Cloud Comets

The comets observed today come from two reservoirs: short period Jupiter families comets (JFCs) which have evolved from the trans-Neptunian region, and long period comets perturbed inwards from the Oort cloud. The JFCs have spent many orbits in the inner solar system, resulting in an evolution of their observable properties due to regular heating well above the sublimation point of water and other volatiles. Some Oort cloud comets are on long period orbits spanning hundreds or thousands of years and have experienced similar modifications as the JFCs. A subset of the Oort cloud comets, called dynamically new comets (DNCs), are entering the inner solar system for the first time and their compositions are likely more reflective of the conditions in the solar nebula where they formed.

Conventional wisdom holds that DNCs can be distinguished from returning Oort cloud comets by their original semi-major axis (1/a0) prior to planetary interactions and by differing rates of activity increase with perihelion distance. However, there is not a single threshold value of 1/a0 at which something can be unequivocally identified as being a DNC, and recent work has shown that the original semi-major axis cannot be identified confidently without accounting for stellar perturbations. Furthermore, the studies which identified trends in activity behavior with perihelion distance were based on data that rarely extended much beyond 3 au, where water ice sublimation becomes less efficient. Today's surveys regularly discover comets beyond 5 au, and discoveries beyond 10 au are becoming frequent.

We propose to modernize the understanding of the activity of Oort cloud comets by conducting observations of the most distant objects. We have ongoing programs that regularly monitor Oort cloud comets as part of a 3-year Key" project using the 1-m telescopes of Las Cumbres Observatory, and via normal semester awards on the 4.1-m SOAR telescope and 4.3-m Lowell Discovery Telescope. We will also incorporate survey data from the Zwicky Transient Facility (ZTF) and the Rubin Observatory's Legacy Survey of Space and Time (LSST) once it begins science operations in 2024. These resources will allow us to obtain a dataset extending to much larger heliocentric distances and acquired in a more uniform manner than previous studies. By monitoring quantities such as absolute magnitude, dust production, and coma color (as a proxy for gas production), we will explore whether there are characteristic trends in the evolution of activity in Oort cloud comets, and if such behaviors can be used as independent diagnostics of previous passage through the inner solar system. When viable, we will also assess coma morphology to investigate activity patterns.

The proposed work's primary focus is new observations of comets, so it is most appropriate for the Solar System Observations program. We will study some of the most primitive objects in our solar system and seek to understand evolutionary differences between new and returning comets, thereby furthering NASA's Planetary Science strategic objective to advance scientific knowledge of the origin and history of the solar system" (2020 NASA Science Plan, p.14). Our results will aid community planning of future detailed observations using the most powerful telescopes, will help determine how to identify comets of interest in LSST data and what follow up observations should be carried out, and will assist in identifying a suitable target for ESA's Comet Interceptor mission.

Conor Nixon/NASA Goddard Space Flight Center
Titan's Atmosphere in Late Northern Summer from the Atacama Large Millimeter-submillimeter Array (ALMA)

MOTIVATION: Titan, largest moon of Saturn, exhibits a dense, hazy atmosphere that appears bland at most visible wavelengths. At longer wavelengths however, Titan's atmospheric complexity is revealed: a plethora of organic molecules are identified through their spectroscopic signatures, and the large-scale motions of the atmospheric circulation, responding to seasonal forcing by sunlight, can be measured. Titan is a unique natural laboratory in the solar system, exhibiting dynamical and meteorological similarities to the terrestrial planets with dense atmospheres (Earth, Venus), and yet chemistry that is much more similar to the reducing atmospheres of the giant planets (Jupiter, Saturn). The study of Titan's atmosphere can uniquely inform us about the complex interplay between organic chemistry and haze production, with the dynamical environment of a slowly-rotating solid 'planet'.

OBJECTIVES: We propose new observations to further elucidate the chemical and dynamical processes in Titan's atmosphere at a previously unstudied seasonal epoch, approaching northern fall and southern spring. These observations, covering 2022-2025, will address a wide array of new fundamental science questions about Titan's atmosphere, divided into three themes: (1) Seasonal Changes in Circulation   How does Titan's global circulation change in the approach to northern fall equinox? Do these changes mirror the seasonal changes seen by Cassini in the approach to southern fall equinox in 2010, but in opposite hemispheres? (2) Global Distribution of Trace Gases   How does the distribution of organic molecules in Titan's atmosphere reflect the changing insolation and dynamical motions? How rapidly do winter concentrations of gases disperse after winter polar vortices break up? (3) Search for New Chemistry   What level of chemical complexity seen by Cassini mass spectroscopy in the upper atmosphere persists into the denser lower atmosphere? What other molecular families exist beyond the ubiquitous hydrocarbons and nitriles, that could be relevant to astrobiology?

METHODS/TECHNIQUES: These objectives will be addressed through a diverse array of observations with ALMA, the Atacama Large Millimeter-submillimeter Array (ALMA). Since its commissioning a decade ago, ALMA has revolutionized long-wavelength molecular astronomy with its simultaneous high spectral and spatial resolution, combined with very high sensitivity. Our observations will cover a variety of spatial resolutions and spectral settings (bandpass, resolution). These will be temporally

spread over four years, to cover approximately half of a season on Titan, including the critical approach to equinox when the circulation begins to reverse.
SIGNIFICANCE: The proposed observations will provide a robust dataset encompassing vertical and spatial variation of Titan's temperatures, gas distributions and winds; a first-of-a-kind set of measurements for this part of Titan's seasonal cycle. At the end of the Cassini mission in 2017 Titan passed through northern summer solstice, and the north polar terrain dotted with seas and lakes passed into late summer, even as the southern polar region was immersed in deep mid-winter. Now as the northern hemisphere approaches the Fall equinox in 2025, the next few years constitute a poorly known part of Titan's seasonal cycle, an opportunity to observe that will not be repeated until the 2050s. These measurements will be archived and made publicly available to constrain photochemical and dynamical models of Titan's atmosphere and thereby greatly improve our understanding of its unique composition and climate in preparation for the forthcoming NASA Dragonfly mission in the mid-2030s.

Glenn Orton/Jet Propulsion Laboratory
All Eyes on Jupiter: Exploring Atmospheric Variability with Thermal-Infrared Observations Supporting Juno and JWST

The goal of this proposal is to enhance the scientific return of the extended Juno mission and James Webb Space Telescope (JWST) observations by providing ground-based, global contextual information from thermal emission. This supplements their limited spatial coverage of Jupiter's atmosphere, tracking its evolution in time and observing over otherwise inaccessible wavelengths, all of which are important for a full characterization of Jovian climate and weather. Thus, we request funding for a unique component of a campaign of ground-based support for the extended Juno mission, as well as for several cycles of JWST observations of Jupiter. We will use state-of-the-art instruments to conduct imaging and spectroscopy in carefully selected spectral regions to (i) determine the 3-dimensional temperature and wind structure and (ii) map aerosols and key gaseous constituents. Our coverage of ~5-20 μm thermal emission will provide the environmental context to interpret their measurements, covering a spectral range missing for Juno and truncated for JWST due to detector saturation. Our observations during this time frame will support mid-infrared regional measurements of Jupiter's Great Red Spot in Guaranteed Time Observations and its South Polar Region in Early Release Science observations. Of additional importance for Juno during this time frame will be providing spatial and evolutionary context to a series of twenty radio-occultation measurements of the temperature structure of Jupiter in its stratosphere through upper troposphere. Documenting the spatial and temporal variability of the atmosphere is an important goal on its own merits, providing critical keys to understanding the energy exchange between the shallow weather layer and the deep interior, a specific target of Juno.

Audrey Thirouin/Lowell Observatory
Mutual events in the trans-Neptunian belt

Small bodies are remnants of the formation of our Solar System, and by studying them we can constrain the early phases of our Solar System and by extension exo-planetary systems. Due to their large heliocentric distances and because they have been minimally altered since their formation, the trans-Neptunian objects (TNOs) are the most primordial small bodies.

Several techniques can be used to characterize the TNOs, but in this proposal research, we aim to apply an underused approach that is widely used for more inner small body populations, but not for TNOs. Our team has identified nine trans-Neptunian binary systems (TNBs) with current/future mutual event seasons. Mutual events are the primary and secondary of a binary system are alternatively eclipsing or passing in front or behind each other. These mutual events are extremely scientifically valuable because it is possible to infer the size, shape, density, and albedo of each component, which are characteristics rarely known for TNOs.

We have designed a 3-year research program to (1) obtain ground-based images of the nine TNBs to derive their rotational and physical properties, (2) use lightcurve modeling for a realistic rendering of the nine TNBs based on ground-based observations, (3) use our modeling to predict the current/future mutual events seasons of the nine TNBs, and (4) observe several mutual events of the TNBs with ongoing seasons to accurately derive the physical parameters of each component and improve our initial modeling.
Our project will be the first extensive observational and modeling study dedicated to nine TNBs with current/future mutual event seasons. We will use the 4.3 m Lowell Discovery Telescope (LDT) and the 6.5 m Magellan Telescope to obtain the rotational and physical characteristics of each system as well as to observe some mutual events to probe the accuracy of our modeling. Both facilities are complementary as they will allow us to observe TNBs in the Northern and Southern Hemispheres with visual magnitudes down to 23-24 mag.

Our project will help ascertain the content, origin, and evolution of the Solar System. This project is strongly related to NASA's strategic plan to support investigations to explore and observe the objects in the Solar System to understand how they formed and evolve. Our project requires a large number of new observations, data analysis, and interpretation and thus is relevant to the Solar System Observations (SSO) program.

New Frontiers Data Analysis Program
Abstracts of selected proposals
NNH21ZDA001N-NFDAP

Below are the abstracts of proposals selected for funding for the New Frontiers Data Analysis Program. Principal Investigator (PI) name, institution, and proposal title are also included. 21 proposals were received in response to this opportunity. On January 25, 2022, 7 proposals were selected for funding.

Ballouz, Ronald/Johns Hopkins University

Comparative Analysis of Craters on the Boulders of Asteroids Bennu and Ryugu

Impact cratering into asteroidal boulders provides a framework for understanding the strength of solid asteroids, the recent surface history of rubble-pile asteroids, the production of regolith on asteroid surfaces, and the population characteristics of small impactors in near-Earth space. High-resolution images and laser altimetry data returned by the OSIRIS-REx mission enabled these types of investigations for the asteroid (101955) Bennu. Similar impact features have been shown to exist on Ryugu. Here, we propose to 1) create a catalog of cratered and disrupted boulders found on the surfaces of Bennu and Ryugu, which includes crater morphometrics, 2) generate a list of guidelines for identifying craters on asteroidal boulders in planetary surface images, and 3) use the catalog with complementary impact experiments to perform a comparative analysis of crater-on-boulders in order to assess differences in intra- and inter-asteroid boulder physical and structural properties.

Our proposed production of a catalog of impact features on asteroidal boulders will be the first of its kind. Even though asteroids have been visited by spacecraft in the past, such as the NEAR-Shoemaker and Hayabusa missions, craters on dense asteroidal material had not been directly observed and measured prior to the arrival of OSIRIS-REx and Hayabusa2 missions to their target asteroids. These data provide access to understanding a fundamental physical process that modifies asteroid surfaces.

The structural properties of the boulders as determined from their surface craters can be used to assess differences in the hydration state and porosity of the population. We will use our catalog to study intra-asteroid boulder diversity and address hypotheses related to the origin of Ryugu's dehydrated state in comparison to Bennu. An inter-asteroid comparison of the response of boulders to impacts will reveal whether Ryugu experienced bulk dehydration (likely set at the time of its formation) or surficial dehydration (likely set during its dynamical evolution from the main asteroid belt).

This study is relevant to the scope of the New Frontiers Data Analysis Program because it enhances the scientific return of the OSIRIS-REx and Hayabusa2 missions by using data obtained during their surveys of Bennu and Ryugu, respectively.

Barth, Erika/Southwest Research Institute

Exploring the Composition of Jupiter's Haze and Cloud Features Observed by JunoCam

The JunoCam instrument has returned spectacular images of Jupiter's poles showing many haze features. Linear streaks have been seen in a methane band placing them at high altitude (~100 mbar level). At the edge of the polar haze are other features with an elaborate "filigree" appearance. A third distinct feature named the "high-altitude cloud" or HAC is thought to be closer to the tropopause (~200 mbar level) but still about 60 km above the more visible cloud layer. The HAC appears to be optically thin and may either be a physically thin layer or the top of a cloud tower. Haze particles in the giant planet atmospheres are important to understand because they affect the opacity of the stratosphere, they serve as condensation nuclei for tropospheric clouds, they provide a means of transporting ices into the troposphere and absorption of solar energy by stratospheric aerosols affects the stratospheric temperature and the location of the tropopause.

Objectives: We will run simulations to explore the composition, size, shape, and altitudes of Jupiter's atmospheric particles to explain the differing appearances of hazes seen in the JunoCam images. The microphysics output will be run through a radiative transfer code to evaluate against JunoCam and JIRAM data.

Methods: The CARMA (Community Aerosol and Radiation Model for Atmospheres) code solves the continuity equation for aerosol particles (vertical transport, coagulation, cloud formation and growth, i.e. microphysics) and calculates their radiative effects in a column of atmosphere. JupiterCARMA is initialized with the Galileo probe temperature-pressure profile and includes species found in Jupiter's atmosphere that reach their condensation temperatures (water, hydrazine, naphthalene, ammonia). It is straightforward to add new species or temperature-pressure data. Involatile organic haze particles are generally prescribed using a production function that represents creation from photochemistry. Other particles involving volatiles are either created through homogeneous nucleation or heterogeneous nucleation onto the haze particles. CARMA tracks particles in discrete size bins and can model the shape as spherical or fractal aggregates.

Significance to NFDAP: The objective of the New Frontiers Data Analysis Program is to enhance the scientific return from New Frontiers missions by broadening scientific participation in the analysis and interpretation of data returned by these missions. Additionally, NFDAP calls for science research that would significantly advance the state of knowledge of the research topic through nondata-analysis tasks, including modeling, that are necessary to analyze or interpret the data. The modeling work we propose will both broaden the scientific participation in the interpretation of Juno mission data as well as provide an interpretation of Jupiter's haze features seen by JunoCam.

Kammer, Joshua/Southwest Research Institute

Reddening of Charon's Poles by Energetic Particles: Extending beyond Lyman-α

One of many discoveries made during the New Horizons flyby of the Pluto-Charon system in July 2015 was the existence of darkened red material centered near the north pole of Charon. The original source of this red material was proposed to be interplanetary medium Lyman-α (IPM Ly-α) photolysis of methane that was frozen seasonally onto Charon's winter polar terrain after escaping from Pluto's atmosphere. However, processing by Ly-α alone is inconsistent with recent exospheric modeling and laboratory experiments, which show Charon's polar methane to be much thicker than Ly-α light can penetrate before being optically absorbed. These new studies, which take into consideration seasonal accretion and sublimation to and from Charon's exosphere through modeling and experiments, conclude that Ly-α photolysis does not produce sufficient complex hydrocarbon 'tholins' near Charon's poles to account for the observed distribution of red material. Instead, the predicted photolytic refractory distribution shows a smooth dependence on latitude, starkly different from the sequestration of red material above ~70°N seen by New Horizons. Moreover, the experiments that simulated Charon's dynamic photolysis conditions, where photolysis occurs concurrently with methane accretion, showed ethane as the primary photo-product, which is not itself sufficiently red to explain the color of Charon's polar cap.

Solar wind could radiolyze the photolytically produced ethane that remains frozen on polar terrain over Charon summer (Tmax~60 K), thereby converting ethane to higher-order (redder) hydrocarbons, but the importance of this process in producing Charon's red material is unknown. We will quantify the contribution of solar wind to the formation of red material on Charon's poles through laboratory experiments and exospheric modeling. We will use the results to estimate the abundance, distribution, and color of complex hydrocarbons produced by solar wind radiolysis and compare with New Horizons MVIC images to determine if the combined effect of IPM Ly-α photolysis and solar wind radiolysis is sufficient to explain the origin of the red polar cap on this enigmatic moon.

We will accomplish 3 major objectives over the 3-year duration of the proposed project. First, we will subject the Ly-α processed methane films to keV proton irradiation (at temperatures from 10 to 60 K) and quantify the changes in composition and color of the refractories with temperature and radiation dose. Second, we will use these laboratory measurements as input for an improved two-species (CH4 and C2H6) Charon exospheric model to estimate the refractory abundance and distribution produced by solar wind over both seasonal and geologic timescales. Third, we will use the predicted spatial distributions of refractory material to produce global maps of Charon's surface as seen in the wavelength channels of the New Horizons MVIC images during the 2015 flyby. Direct comparison of our model output with New Horizons images will reveal the relative contribution of processing by solar wind on the formation of Charon's red poles.

The proposed work is directly relevant to the NASA New Frontiers Data Analysis Program as it would be an investigation "utilizing or enhancing the utilization of data obtained by the New Frontiers missions". This data includes New Horizons images from the Multispectral Visible Imaging Camera (MVIC) that operates over a bandpass from 0.4 to 0.95 μm. Additionally, this proposal "broadens scientific participation in the analysis and interpretation of New Horizons data" by enabling collaboration and research efforts by scientists external to the New Horizons team.

Molaro, Jamie/Planetary Science Institute

Timescales for boulder evolution from thermal fatigue and impacts on asteroid (101955) Bennu

Recent works by the proposing team show the discovery of boulder morphologies on asteroid Bennu that are consistent with exfoliation, i.e., the flaking of thin layers or shells of material from boulder surfaces and one of the most distinctive signatures of thermal fatigue. This is the first time this mechanical weathering process has been observed on an airless body surface, though previous studies had hypothesized its importance. Further, this process is thought to contribute to the ejection of particles from Bennu's surface that have been observed by the Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer (OSIRIS-REx) spacecraft. Impacts forming small scale craters ("bullet holes") are also known to cause boulder degradation on Bennu, though the relative rates between the two processes is currently unknown. Understanding the contribution of both impacts and thermal fatigue to boulder breakdown and regolith production is critical to characterizing the evolution of Bennu's surface and boulder size-frequency distribution (SFD) and has significant implications for the broader airless body population.

The proposed work consists of four tasks: 1) For a number of study locations, we will use high-resolution images to search for boulders which show morphological evidence of both bullet holes and fatigue-driven exfoliation flakes. The SFD distribution of small craters on Bennu has already been quantified, which will allow us to place constraints on the boulder surface ages and therefore the formation timescale of their exfoliation flakes. Surface ages will be further constrained by searching spectral data for aliphatic organic signatures at each site. 2) We will perform 3D finite element modeling of the boulders with exfoliation and impact signatures in order to quantify the amount of thermally induced stress they experience. The results of these simulations, combined with the formation timescales from Task 1, will allow us to model thermally induced crack propagation and constrain the rate at which exfoliation flakes develop over time. This will provide key insight into the rate of boulder degradation relative to impact processes. 3) We will survey the location and thickness of exfoliation flakes more broadly across Bennu's surface using images and altimeter data for our study locations. We will analyze the exfoliation and impact features with respect to boulder size, type, geographical distribution, and other attributes to understand mechanical weathering on Bennu in a more global context. 4) With the insights provided by Tasks 2 and 3, we will assess how both impact and exfoliation processes alter the size and shape of boulders over time and drive the evolution of Bennu's surface and boulder SFD.

The proposed work is directly relevant to the objectives of the New Frontiers Data Analysis Program as defined in Appendix C.7 of ROSES-2021, including to "enhance the scientific return from New Frontiers missions by broadening scientific participation in the analysis and interpretation of data returned by these missions" and to "conduct scientific investigations using…data obtained by the New Frontiers and Hayabusa2 missions," and will be accomplished using OSIRIS-REx data available in the Planetary Data System 30 days prior to the proposal due date, per ROSES-2021 C.1-3.5. Furthermore, this research addresses many "key questions" and "specific objectives" associated with the "science goals" outlined by the 2013-2022 NRC Planetary Science Decadal Survey, including: "how have the myriad chemical and physical processes that shaped the solar system operated, interacted, and evolved over time" (p. 71, key question 10), and "determine the effects and timing of secondary processes on the evolution of primitive bodies" (p. 89, objective 3, science goal 1), and "characterize planetary surfaces to understand how they are modified by geologic processes" (p. 113, objective 3, science goal 1).

Santos Costa, Daniel/Southwest Research Institute

Understanding the high-energy electron dynamics at Jupiter using Juno MicroWave Radiometer (MWR) Data

We propose to determine the mechanisms of how multi-MeV electrons populate different regions of Jupiter's magnetosphere and how they evolve as a function of time.

Jupiter's radiation belts were discovered in the 1950s from radio measurements. While Pioneer 10 & 11 confirmed the presence of high-energy electrons throughout the magnetosphere in the 1970s, variations were uncovered from ground-based observations of Jupiter's radiation-belt (or synchrotron) emission in the 1970s-2000s. The Galileo mission (1995-2003) did not provide insights into the electron belts variability. Our current inability to understand the dynamical behavior of the electron belt has been directly linked to the lack of ancillary observations during in-situ measurements.

Since 2016, Juno has been revisiting Jupiter's magnetosphere and traveling through uncharted regions. Information on high-energy electrons is inferred from penetrating radiation and synchrotron emission measurements. Juno's simultaneous in-situ and remote sensing observations provide a unique opportunity to perform new science that would also support previous measurement interpretations. We propose to use Juno data to address 3 science questions:

1. What are the drivers of Jupiter's electron radiation belts variability on month-to-year time scales?
We propose to use Juno/MWR measurements of Jupiter's synchrotron emission to reconstruct the temporal variations of the inner electron belt for the period 2016-2021. A trend of ~50 years will be examined by combining Juno data with ground-based observations from 1970-2018. Correlations with heliospheric parameters (e.g., solar wind ram pressure, cosmic ray fluxes) will guide our simulation of Jupiter's synchrotron emission using a simulator that accounts for the influence of physical parameters on electron belts distribution. The simulated trend will enable us to understand how source and transport mechanisms are coupled over long periods of time for the electron belts.

2. What are the mechanisms responsible for synchrotron radiation at L-shell of ~6-9?
Juno/MWR measures a source of synchrotron emission in the middle magnetosphere, consistent with penetrating radiation levels in Juno instruments for this region. We propose to simulate MWR observations for the 6-9 L region, using a diffusion theory model of radiation belts to compute different electron distributions to be incorporated into our simulations of synchrotron emission. Our results will determine whether adiabatic transport, wave-particle gyro-resonance interaction or the plasma sheet are responsible for the radio emission at L~6-9. Galileo particle data will also be used to support understanding the variability of this region.

3. How are high-energy electrons transported towards Jupiter's auroral acceleration regions?
Features in Juno/MWR data suggest that flux tubes connected to Jupiter's main aurora are populated with field-aligned high-energy electron distributions (FADs). We will simulate MWR observations when Juno is above the auroral regions and confirm FADs by testing different electron distributions in our simulations. Using in-situ data and a diffusion theory model of electron belts, we will then determine the role of wave activity and injection events in different magnetospheric regions to explain the inferred particle distributions.

We will mainly use Juno/MWR and JADE data, which are publicly available at the PDS for Juno's first

30 orbits, for our investigation of Jupiter's electron belt. Heliospheric and data from past planetary missions are also available at the PDS and at other public domain databases (e.g., SPDF). Wave data from planetary missions will be used to support our numerical findings.

The proposed study is relevant to NFDAP as it would analyze Juno data of high-energy electrons from the prime mission. The expected results would enhance our fundamental knowledge of the harshest radiation-belt environment known in our solar system.

Smith, Howard/Johns Hopkins University

A novel view of Jovian moons: Probing Io and Europa neutral torus regions with Energetic Neutral Atom imaging

Science goals and objectives:
The Jovian system is very intriguing with extremely different magnetospheric particle sources ranging from the volcanic Io to the frozen world of Europa. Of interest to this proposed research, neutral tori are formed when particles escape into a population that co-orbits with the moon. Tori distributions and compositions are a direct result of the satellite composition and source mechanisms. Thus, understanding these features can often provide critical insight into aspects of these source moons that might be difficult to observe directly. As the dominant source of particles to Jupiter's magnetosphere, Io is of particular importance. However, this source is not well understood with total rate estimates and source mechanisms (ex. volcanic vs. sublimation) under debate. Other moons, such as Europa, also appear to be forming neutral tori. Detection and characterization of these tori could provide significant insight into these satellites with regard to composition, processes, interactions and potential habitably.

Unfortunately, neutral tori are often difficult to detect directly. Fortunately, [1] recently confirmed an innovative method of remotely detecting neutral tori (and their sources) using the Juno JEDI high-energy charge particle instrument. For this proposal, our goal is to analyze this unexploited dataset to provide unique insight into Io and Europa neutral tori and how they interact with Jupiter's magnetosphere. More specifically, to accomplish this scientific goal, our objectives are:

1) Characterize the Io and Europa neutral tori using ENA observations
2) Constrain Europa & Io sources
3) Search for possible additional neutral tori

We propose a detailed spatial and temporal analysis of all Juno JEDI data for the presence of Energetic Neutral Atoms (ENAs) and their origins. We will then apply 3D modeling to characterize the neutral tori and required satellite source constraints. Although Juno does not have an ENA detector, Mauk et al. (2020) discovered that while the Juno JEDI instrument is designed to measure energetic charged particles, some ENAs are also detected. ENAs are likely the result of charge exchange interactions where this resulting particle essentially travels along a straight line of sight to the instrument providing a method of remotely sensing and characterizing neutral tori. We will apply this data analysis technique to identify and analyze all observations that originate from the Europa and Io orbits (and the absence of these detections) with in situ charged particle observations of these regions where possible. We will also search for any observations that coincide with other satellite orbits. Next, we will apply an existing, validated 3-D Monte

Carlo neutral particle model of the neutral tori. Our data analysis results will provide essential spatial and temporal constraints for Io and Europa neutral tori forward modeling to determine what moon source rates and distributions are required to reproduce the observations. This will also provide a 3D representation of each tori with respect to time. The result will be a much more accurate understanding of Europa and Io neutral tori and the implications for source mechanisms and magnetospheric interactions. In the event that we can detect other neutral tori, these results will also provide insight into previously undiscovered neutral tori.

Relevance
This proposed work is directly relevant to the NFDAP program (analysis and modeling of New Frontiers Mission data) as we propose to analyze Juno data to gain critical insight into Io and Europa neutral tori and their source mechanisms.

Young, Eliot/Southwest Research Institute

Formation of varied types of aerosols on Pluto

1. Goals and Objectives of Proposed Work

The overarching goal of the proposed work is to understand haze formation and evolution on Pluto. Recent work has highlighted some open questions regarding Pluto's aerosols, which we adapt to two proposal goals.

Goal 1: New Horizons images from different phase angles show evidence for at least two types of aerosols on Pluto: fractals and non-fractals. The first project goal is to understand the formation and distribution of and transition between fractal aerosols and non-fractal aerosols. This goal is important because Pluto serves as a laboratory in which we can investigate two types of basic processes: the formation of fractal aggregates from monomers and condensation of volatiles onto those aggregates.

Goal 2: The New Horizons UV solar occultation experiment showed evidence for haze at altitudes as high as 300 km (limited by the experiment's SNR), and LORRI and MVIC imaging showed scattering from aerosols. The second project goal is to determine fundamental properties of Pluto's haze from these observations: what are the haze precursors, what are monomer sizes that make up fractal aerosols, what are settling and coagulation rates, and how does Pluto react to solar flares and the solar cycle. This goal is important not only because it provides an understanding of basic haze-formation processes on Pluto, but also because it helps us understand comparative haze formation processes with respect to other N2 atmospheres, like Triton and Titan and some exoplanets.

The study of aerosol formation processes is significant on several fronts: aerosols affect energy depositio, atmospheric dynamics and atmospheric escape on Pluto, and haze formation and sequestration on the surface plays a key role in the inventory of organic molecules that accumulate on Pluto (or similar bodies).

2. Approach and Methodology

The heart of this project is the comparison of New Horizons observations to results from four modeling applications: FISM-II (modeling solar output at UV wavelengths), GLOW (modeling the spectrum of superthermal electrons in Pluto's atmosphere), KINETICS (modeling photo- and electron-dissociation processes and recombination chemistry in Pluto's atmosphere) and CARMA (modeling haze coagulation and vertical transport). These four applications work together to produce simulated haze distributions that can be compared to New Horizons data sets: LORRI and MVIC pre- and post-encounter images and UV and radio occultation profiles. A radiative transfer code (e.g., PYDISORT, adapted from Titan to Pluto) will be used to generate simulated images from model atmospheres -- images that can be compared to observations. It is expected that the modeled haze distributions will be sensitive to a suite of interesting-but-currently-unknown parameters, such as monomer sizes, altitude and rate of monomer formation, assumed amounts of trace gases (i.e., which trace gases are important bottlenecks to haze formation), particle fall velocities and altitude and rates of condensation onto fractal "seed" particles.

3. Appropriate Fit between Proposed Work and the Program Element

Section 1.1 of the NFDAP AO states: "The objective of the New Frontiers Data Analysis Program (NFDAP) is to enhance the scientific return from New Frontiers missions by broadening scientific participation in the analysis and interpretation of data returned by these missions." The NFDAP program element work is an appropriate vehicle for this reseach because the New Horizons observations are a critical part of this project. Conversely, this work is within the scope of the program element because it examines New Horizons data to determine haze formation/evolution scenarios on Pluto.

Lunar Data Analysis Program
Abstracts of Selected Proposals
(NNH21ZDA001N-LDAP)

Below are the abstracts of proposals selected for funding for LDAP. Principal Investigator (PI) name, institution, and proposal title are also included. 35 proposals were received in response to this opportunity. On June 17, 2022, 7 proposals were selected for funding.

Jeffrey Andrews-Hanna/University of Arizona
A GRAIL gravity investigation of lunar volcanism and magmatism

The history and nature of volcanism on the Moon provide critical information on its internal evolution. Lunar volcanism is a direct product of the thermochemical evolution of the interior, and has been the dominant endogenic process modifying the surface through time. However, we can only directly observe the youngest volcanic materials on the surface, leaving significant uncertainties in the nature of early volcanism, the thickness and volume of extrusive materials, and the volumes and distribution of intrusive materials. This study will use GRAIL gravity data to shed new light on mare volcanism and the volumes of both intrusive and extrusive materials emplaced throughout lunar history.

The first task of this study will examine a surprising aspect of mare volcanism. While the gravity signatures of a small number of large craters (diameters d>90 km) buried beneath the maria are observed, there is no sign of the large number of smaller craters (d<90 km) that would be expected for a volcanically flooded ancient cratered surface. GRAIL gravity data can resolve volcanically flooded impact craters with diameters as low as 11 km, yet there is a striking deficit of such craters. A model of the gravity field of volcanically flooded cratered farside terrain bears no resemblance to the nearside maria. These observations lead to the inescapable conclusion that a large population of craters with diameters <90 km was somehow erased from the pre-mare surface before or during the volcanic eruptions. Task 1a will compare forward models of the gravity field of volcanically flooded cratered terrains with the mare to constrain the nature of the crater erasure. Task 1b will test a set of hypotheses to explain the lack of small craters, including a higher density substrate or lower density mare layer, thermal erosion by lava, viscous closure of pore space, and the presence of an ancient layer of volcanic materials that prevented smaller impacts from excavating into the underlying feldspathic crust.

Task 2 is aimed at constraining the volumes of extrusive and intrusive volcanism over time. The total volume of igneous materials and the relative volumes of extrusive and intrusive materials provide an important constraint on the thermochemical evolution of the lunar interior. However, this volume remains poorly constrained and previous estimates vary widely. Task 2a will use gravity and topography data together with flexural loading models to constrain the thickness of the maria. Task 2b and 2c will use inversions to constrain the volume of intrusive materials both associated with floor fractured craters and elsewhere. Task 2d will use the results of these analysis to quantify the inventory of intrusive and extrusive materials on the Moon. Task 2e will focus on the density anomalies in the south polar region. This region, encompassing the future Artemis landing site area of interest, is part of a zone of large magnitude, short wavelength gravity and gravity gradient anomalies along the rim of the South Pole-Aitken basin. The subsurface density anomalies at the source of these gravity anomalies are likely related to post-impact intrusive activity, as also observed around smaller basins such as Orientale. This task will characterize these density anomalies in advance of future exploration by Artemis.

The proposed work will analyze GRAIL gravity data and LOLA topography data in an investigation of lunar volcanism, and thus is highly relevant to the goals of the LDAP program. The proposed work consists of direct data analysis and data-driven modeling in order to better analyze and interpret the data. Collectively, these tasks will shed new light on the volcanic history of the Moon.

William Farrand/Space Science Institute
Examination of potentially hydrated lunar volcanic terrains using orbital imaging spectrometer data

One of the exciting discoveries coming from the Moon Mineralogy Mapper (M3) on-board the Indian Chandrayaan-1 orbiter was the finding of a down-turn in reflectance going towards 3 microns that has been attributed to the presence of adsorbed OH and/or H2O. Some studies have shown a latitudinal and diurnal dependence on the presence and strength of this feature. Other studies have shown that certain terrains at lower latitudes have increased strength of this feature. Among these are certain lunar pyroclastic deposits and also various lunar red spots" that have been determined from LRO Diviner to nominally be products of silicic volcanism.

However, the ability to detect and characterize the OH/H2O absorption in M3 data depends critically on the correction of the M3 data for thermal emission since the radiance observed from the lunar surface by M3 in wavelengths longer than approximately 2 microns consists of both reflected and emitted radiance. A widely used empirical thermal correction that has been used to provide level 2 reflectance data to the PDS was used in studies that found increased strength of the OH/H2O absorption in the nominally lunar silicic volcanics. An alternate empirical approach to thermal correction, based on lunar sample reflectance studies, was used in the assessment that a number of glass-rich lunar pyroclastic deposits showed increased strength of the OH/H2O absorption. An alternative physics-based thermal correction that accounts for the anisothermal nature of the lunar surface has cast doubt on the increased hydration associated with the putative silicic volcanic domes and further work with this approach has shown, at a minimum, weaker absorptions associated with the glassy lunar pyroclastic deposits.

Results from the physics-based thermal correction approaches are largely preliminary and have not been applied in a systematic way to the putatively hydrated volcanic terrains. Using the physics-based thermal correction methodology, a systematic examination of these potentially hydrated volcanic terrains is proposed. These corrections will be applied to PDS-archived M3 data. Also, data from the Chandrayaan-2 Imaging Infrared Spectrometer (IIRS) has recently become available to the broader planetary science community. This instrument has a wavelength range that extends from 0.8 to 5 microns. Thus, covering the full 3 mm OH/H2O absorption. It is proposed that where IIRS data is available over the features of interest that it be used as well to complement the M3 data and provide added information on the nature of the 3 micron absorption.

This work will be carried out through four tasks. 1) Adapt an existing physics-based thermal correction approach to work with both M3 and IIRS data. 2) Examine of M3 and IIRS data to assess the presence/strength of any OH/H2O absorption associated with a selected set of regional and localized lunar pyroclastic deposits. 3) Carry out a similar study over lunar red spots"/silicic domes that have been described as having an associated 3 micron absorption feature. 4) Use data from different local solar times and band shape information to assess if hydration is potentially endogenous or if it shows diurnal or band shape variations indicative of exogenous origin.

This proposed research is relevant to the Lunar Data Analysis Program (LDAP) in that it will use data sources called out in the LDAP announcement, specifically M3 data, data from Chandrayaan-2, LRO Diviner data, and other lunar orbital datasets. The understanding of volatiles on the lunar surface is one of the highest priority science objectives called out in community studies of lunar science priorities and this study will improve that understanding.

Sean Gulick/University of Texas, Austin
Integrated Measurements and Analysis of Geophysics of Schrödinger (IMAGES)

Impact cratering drives upwards motion of crustal or mantle materials, affects physical properties of target rocks, and mobilizes fluids. Large impact basins can generate global deposits, store deeply sourced rocks in peak rings, and be the site of post-impact hydrothermal and volcanic processes. Impact basin floors can be geologically complex due to a mixture of impact melts, impactoclastic products, and later modifications, such as volcanic events and faulting. Subsurface imaging can assess these structural and depositional processes thereby enabling greater insights from surface mapping, especially where insights into physical properties of surficial geologic units can be quantified and assessed. Recent geophysical imaging and scientific drilling of the well-preserved Chicxulub impact basin on Earth has strongly supported the geologic implications of hydrocode models of impact formation wherein peak rings are formed from dynamic collapse of over-heightened central uplifts and represent sites likely to exhibit outcrops of deep crustal rocks for future sampling. Physical properties of the drilled lithologies proved fundamentally altered by impact yielding low densities and high porosities, a result consistent GRAIL findings of a broadly porous lunar crust.

Here, we propose to merge new radar products and analysis of the Kaguya Lunar Radar Sounder (LRS) with data from the Kaguya Terrain Camera (TC), Moon Mineral Mapper (M3), Lunar Reconnaissance Orbiter (LRO) Wide Angle Camera (WAC) and Lunar Orbiter Laser Altimeter (LOLA), and GRAIL to explore geologic diversity, depositional processes, subsurface structure, and identify potential resources and geohazards of the Schrödinger impact basin. With a 5 MHz central frequency, JAXA LRS can image the subsurface to 100s of meters.

This proved effective in regions of flat topography, where subsurface reflections caused by differences in electrical permittivity were imaged, but challenging in regions surrounded by greater topography causing surface clutters to mislead the identification of subsurface returns. Furthermore, leveraging the reflectivity of the LRS surface-return to investigate decametric surface properties for insights into depositional processes has never been carried forward. We propose to apply the Radar Statistical Reconnaissance (RSR) technique to differentiate the scattering/incoherent component of the LRS surface returns from the coherent portions of the signal, and to conduct radar simulations to discriminate internal reflectors from surface clutters and assess the contribution of roughness scattering to the surface reflectometry. Resultant profiles and maps, which are sensitive to the subsurface geology, can be jointly analyzed with image, spectral, and topographic data, and GRAIL high-resolution products, to: 1) conduct a next stage interpretation of the Schrödinger impact basin stratigraphy, 2) search for impact-generated but shallow buried features such as the non-exposed portions of the terrace zone and peak ring structures, 3) explore the thickness/physical properties of impact deposits and post-impact volcanic units, and 4) examine cross-cutting structural features (scarps and grabens) for potential origin and hazard. With these new data products and geologic interpretations, the Payloads and Research Investigations on the Surface of the Moon (PRISM) teams will have crucial information about the geology of future landing site(s) in Schrödinger basin, where the Farside Seismic Suite (FSS) and Lunar Interior Temperature and Materials Suite (LITMS) are planned for 2024-2025 deployment. Seismic structure and electrical properties from these instrument suites represent a calibration opportunity for using radar data within Schrödinger basin and lunar targets more generally, for which this proposal represents critical groundwork in radar processing, clutter simulation, statistical analysis, and multi-sensor integrated geologic mapping.

Peter James/Baylor University
Bulk density of the Moon's silicic volcanic emplacements

This two-year project will quantify the mean bulk density of the Moon's silicic volcanic structures to a depth of a few kilometers. The project will use remote sensing data and the lunar gravity field to characterize five prominent sites: (1) Hansteen Alpha, (2) Lassell Massif, (3) Gruithuisen Domes, (4) the Aristarchus Crater Complex, and (5) Compton-Belkovich Volcanic Complex. The proposed work will provide insight into the unusual nature of these enigmatic structures, improving our understanding of the diversity of lunar volcanism and providing timely, essential context for imminent exploration targets.

Task 1 encompasses an integrated remote sensing analysis of the five study regions to define spatial boundaries and establish compositional constraints critical for interpreting gravity models. Lunar silicic materials exhibit several compositional distinctions that are well-captured by publicly-available remote sensing data. For example:

- Silica content affects the position of the Christiansen Feature (CF) in thermal infrared emissions. CF positions across the lunar surface are well-captured by the Diviner Lunar Radiometer (~200 m/pixel).
- Lunar silicics exhibit relatively high albedo, which is captured in high spatial resolution (~100 m/pixel) by a number of instruments including the Lunar Orbiter Laser Altimeter (LOLA) and the Lunar Reconnaissance Orbiter Camera (LROC).
- These materials are relatively low in Ti+Fe, which have been estimated in high spatial resolution by the Kaguya Multiband Imager, LROC, and the Clementine Ultraviolet-Visible Spectrometer.
- Lunar silicics are associated with an enhanced concentration of volatiles, which are captured as surface hydration in high-resolution (~100 m/pixel) Moon Mineralogy Mapper (M3) data.
- Additional mineralogical information (mafic abundance, composition, optical maturity, etc.) is available in high spatial resolution in M3 and Kaguya data.
- Additional low-spatial resolution (e0.5 degrees / pixel) elemental abundances (including Th, K, Fe, Ti, H, etc.) are captured in Lunar Prospector data.

These various data sources will be integrated using ArcMap software, establishing important spatial constraints for gravitational analyses in Task 2.

Using the spatial boundaries established in Task 1, Task 2 will calculate bulk density at each of the five sites. This task will utilize the gravity field and associated clone fields derived from the Gravity Recovery And Interior Laboratory (GRAIL) data set, along with laser altimetry data from the Lunar Orbiter Laser Altimeter (LOLA). A spectral band-pass will control the depth sensitivity of the investigation and avoid gravitational contributions from the mantle and deep crust. Predicted gravity anomalies from finite-amplitude LOLA topography can be calculated; predicted and observed GRAIL gravity anomalies will both be downward-continued to the height of local topography.

Comparison of the predicted and observed gravity anomalies with a weighted regression yields a best-fit bulk density for the sensitivity zone. The pore-free density (i.e., grain density) may also be estimated with the incorporation of an exponential porosity profile into the finite-amplitude topographic gravity calculation. The grain density is influenced by composition and particularly the mafic abundance; any mismatch with the surface compositions inferred in Task 1 will be scrutinized. Clone fields from GRAIL will allow the uncertainty of this analysis to be rigorously quantified.

By applying identical methodologies to each of the locations described above, this project will directly compare silicic sites and will quantify the diversity thereof. This will provide crucial context for the history and structure of high-priority lunar exploration destinations.

Kirby Runyon/Johns Hopkins University
Lunar Impact Melt Deposit Stratigraphy

The timing and duration of early solar system bombardment has profound implications for the early evolution of not only the Moon, but for most other solar system worlds. The Moon is the solar system's unique witness plate to the Earth-Moon system in which the geologic record from 3-4 Ga is preserved and exposed at and near the surface. While determining the age of the oldest (South Pole-Aitken) and youngest (Orientale) of the large basins would bookend the epoch of heavy bombardment (in particular whether it was a spike, sawtooth, smooth decline, etc.), there is value in determining the temporal spacing (stochasticity) of basin formation for the Moon. Superposition relationships between basins, craters, and other geologic units reveals the relative timing of basin formation, but absolute ages are only available for basins for which we have dateable impact melt from known basin provenance. Future landed missions are needed to do in situ age determination or to return samples for lab-based age determination. Dating cooled impact melt deposits with a known basin provenance is the crucial lynchpin, though it is often obscured through impact gardening with other lithologies or buried in mare flood basalts. However, complex craters which superpose the impact melt deposit of larger basins uplift deep portions of the impact melt deposit in their central peaks. This lifts the lithology of interest above contaminating or obscuring lithologies (such as mare basalt flows), and there is evidence that the relatively gentle shocks of central peak uplift do not reset the ages of these rocks. Thus, the central peaks of craters likely preserve the radiogenic age of the pre-impact lithology.

We propose to use Moon Mineralogy Mapper (M3) hyperspectral data and Lunar Reconnaissance Orbiter Narrow and Wide Angle Camera (NAC and WAC) to compositionally and morphometrically map the area of and around central peaks to inform future sampling locales. From these data, we would construct geologic cross sections of the near-surface stratigraphy: an antecedent for contextualizing eventual sampling. Describing and inferring the geology and stratigraphy in this way would inform whether the peaks would be suitable places for future missions to date the superposed basin. Basins with appropriate superposing complex craters or other suitable landforms (in parentheses) that we propose to study could include Nectaris (Theophilus), Mädler (Piccolomini), Fecunditatis, (Langrenus), Smythii (Neper), Bel'kovich (Hayn), Moscoviense (Belyaev), Poincaré (Cracked, lobate deposit on interior, northern rim lava overflow from Poincaré Z), Orientale (Maunder and Maunder formation [comparison between uplifted impact melt sheet and melt sheet]), and Grimaldi (Floor).

While our research would inform potential sampling locations on the Moon for constraining the timing and duration of inner solar system bombardment, implications would be far reaching beyond the proposal's scope. For instance, life's emergence on Earth 3.8 Ga occurred in an era when the heavy bombardment of the inner solar system was waning but perhaps not over. What was the asteroid and comet impact environment on early Earth during life's emergence? Our planet's geologic history from this time has been largely destroyed and replaced with the record of more recent events. However, while the lunar basin forming record would not be the same as for Earth, it would be representative as a proxy record for determining Earth's environmental conditions during life's emergence. Our results could also inform sampling locations to test whether and to what degree impact melt sheets differentiate following formation.

Before we can confidently begin to address such important questions for solar system science, we must first map out and characterize potential areas on the Moon that can begin to answer these questions. In do doing, we simultaneously and directly addressing other outstanding lunar science questions.

Norbert Schorghofer/Planetary Science Institute
Mapping of Surface and Subsurface Cold Traps for Ice and Supervolatiles

The abundance and distribution of water ice in the lunar polar regions is a science and exploration priority. In this project, we propose to use Diviner surface temperature data to delineate ice sequestration mechanisms, cold traps of supervolatiles, and limits to lunar spelaean ice.

1) Maps for ice sequestration mechanisms in the north polar region: Water ice might be sequestered due to cold trapping, burial, or thermal pumping. Recently developed methods that were used to produce maps of these ice sequestration mechanisms for the south polar region will be applied to the north polar region.

2) Supervolatiles: Time-dependent surface temperatures, including their seasonal variations, will be used to produce accurate maps of supervolatiles in both polar regions. The vapor pressures and phase diagrams of volatile species will be reviewed.

3) Lunar ice caves: Lunar caves might contain ice. We will use temperature data to determine geographic limits to the potential occurrence of spelaean ice on the Moon.

Methodology: Diviner bolometric temperatures over nearly 12 years will be processed and sorted into diurnal and seasonal bins for equal time coverage. To reliably extrapolate sublimation rates of supervolatiles, a literature review of vapor pressures will be conducted. Numerical models will be used to estimate subsurface temperatures using the Diviner surface temperatures as input.

Significance: LDAP supports scientific investigations of the Moon using publicly available LRO data, and the identification, distribution, and characterization of volatiles on the Moon is a high priority area.

Kelsi Singer/Southwest Research Institute
Anatomy of a Secondary Crater

Motivation & Investigation Goals: Impact events are one of the major geologic processes shaping the surface of the Moon. Ejecta from impacts redistribute material across the Moon, impacts excavate and mix material into the subsurface material, and crater densities are used to understand the ages of various geologic units.

Secondary craters provide a record of the fragmentation and ejection of material that occurs during planetary-scale impacts. They also need to be accounted for when estimating crater retention ages. We propose the first in-depth, extensive study of secondary crater morphologies.

While the attributes of secondary craters are often generally cited (e.g., v-shaped ejecta, shallow depth-to-diameter ratios, asymmetrical shapes) most of those aspects have very few direct measurements. In addition, general ideas/theories exist for why secondary craters have these aspects, but most have not been supported by physical measurements. For example, the v-shaped ejecta is hypothesized to be from interference of the ejecta curtains of adjacent secondary craters during formation, but there are secondary craters with v-shaped ejecta that are not near any other distinctive secondary craters.

We will use observations of secondary craters on the Moon to place constraints on impact cratering physics and to improve our understanding of the distribution of ejecta and secondary craters created by large lunar primary events (~10-km-scale or greater).

Proposed Work & Methodology: The Moon provides an excellent natural laboratory to investigate impact physics and cratering as a geologic process. We will make a number of measurements using Lunar Reconnaissance Orbiter (LRO) Narrow and Wide Angle Camera images (LROC NAC and WAC) and Kaguya Terrain Camera. We will also make topographic measurements using both PDS-available digital terrain models (DTMs) and topographic products we will create ourselves.

Mars Data Analysis Program
Abstracts of Selected Proposals
(NNH21ZDA001N-MDAP)

Below are the abstracts of proposals selected for funding for the Mars Data Analysis program. Principal Investigator (PI) name, institution, and proposal title are also included. 66 proposals were received in response to this opportunity. On May 9, 2022, 19 proposals were selected for funding.

Hassanali Akbari/Catholic University Of America
Origins and effects of accelerated electron populations at Mars
21-MDAP21_2-0007

Recent studies based on measurements by the Mars Atmosphere and Volatile Evolution (MAVEN) spacecraft have uncovered that accelerated electron populations with energies of up to 1keV are present in abundance in the plasma environment surrounding Mars. The accelerated electrons are observed at altitudes as low as 150 km, indicating that they likely interact with the Martian upper atmosphere. They carry enough energy flux to produce visible aurora. Observations of energetic particle acceleration and aurora---which are often considered as features of magnetized planets---at Mars are very significant and deserve focused investigations.

Preliminary results show that accelerated electron populations have distinct signatures, indicating that different acceleration mechanisms may exist in different regions of the Martian plasma environment. One goal of this proposal is to categorize a large number of observations based on their characteristic features in order to gain insight into the nature of the acceleration mechanisms. Newly published results indicate that significant fluxes of accelerated electrons are trapped within the loops of the Martian crustal magnetic field without instantaneous access to the collisional region of the atmosphere. Another goal of this study is to investigate whether and under what conditions the trapped energized populations can escape the crustal fields and precipitate into the upper atmosphere. Given the energy flux that they carry, and the localized nature of cusp-like regions associated with the crustal fields, precipitation of the trapped electrons is likely to cause significant modifications of the local ionosphere. This study will investigate such modifications. The proposed research will rely on the analysis of existing MAVEN data and supporting numerical modeling to address the following Science Questions:

1. What processes are responsible for accelerating electrons in the Martian plasma environment?
2. How do energy and pitch angle distributions of the electron populations that are trapped inside the crustal magnetic fields evolve in time and space? And what portion of the energy flux is deposited into the Martian upper atmosphere?

3. What is the local response of the Martian ionosphere to precipitation of accelerated electrons?

Methodology:

An existing database of accelerated electron populations will be revisited to sort the observations based on a number of features, such as peak energy, temperature, pitch angle distribution, proximity to current sheets and magnetic crustal fields, solar wind conditions, etc. Categorizing the observations in this way would help identify the underlying acceleration mechanisms, addressing Science Question 1. Science Question 2 will be addressed using modeling that will be constrained by observations. A realistic model of the Martian crustal magnetic field will be employed. Accelerated electron populations will be injected into the crustal fields and their evolution will be monitored as a function of time. Science Question 3 will be addressed via direct analysis of MAVEN observations. Potential signatures of particle precipitation---such as sudden change of plasma density, electron temperature, the ratio of various ion species, etc.---will be identified and correlated with particle precipitation events.

Relevance:

The proposed study, which heavily relies on the analysis of existing MAVEN data, will enhance the scientific return from the MAVEN mission. The proposed research will investigate one of the most fundamental topics in space plasmas (i.e., particle acceleration) and advances our understanding of the physical processes that are active in the Martian ionosphere and contribute to its dynamics and energetics.

Joseph Battalio/Yale University
Diagnosing the Causes of Regional Dust Storms Using the Mars Dust Activity Database
21-MDAP21_2-0009

The impact of dust activity on the large-scale, present-day climate of Mars is well known and is important to understand for spacecraft operations. Regional dust activity usually occurs in two or more events each year, often controlled by the timing of large-scale, traveling atmospheric waves. However, many aspects of dust storm climatology are poorly understood. For example, it is unclear why one or two specific waves out of a regular train of traveling waves flush equatorward to trigger regional dust events, while other waves and their associated dust lifting remain trapped near the poles. Additionally, the relationship between the observed morphology of regional dust events from orbit and the associated atmospheric dynamics driving those structures remains poorly constrained.

With the advent of Martian reanalysis datasets, traveling waves and their observed dynamics can be connected to the occurrence of dust activity as shown in the Mars Dust Activity Database (MDAD). In combination, these datasets can verify the position of fronts in relation to visible structures in dust activity, which is needed to validate Martian global climate models. The objective of the proposed work is to link the dynamics, timing, and evolution of transient atmospheric waves to their associated cloud and dust activity to better understand some of the mechanisms that organize dust lifting and transport across hemispheres.

The proposed work will document the lifecycle of midlatitude traveling waves to link the timing of dust activity to associated atmospheric dynamics. The atmospheric dynamics for particular periods of large dust storms will be diagnosed using the Open Access Mars Assimilated Remote Soundings and Ensemble Mars Atmosphere Reanalysis System reanalyses, each of which rely on assimilation of Mars Global Surveyor and Mars Reconnaissance Orbiter observations. These data will be compared to observed dust activity from MDAD to develop a conceptual model of the structure of midlatitude, transient atmospheric waves that promote dust lifting and quantify the average dynamical atmospheric state enabling dust transport. The increased understanding provided by linking the transient wave lifecycle to the organization of dust lifting and morphological evolution will enable the inter-comparison of dust events across season and year. Further, connecting dust storm activity to their incipient transient waves will allow for the examination of why some storms flush across hemispheres by evaluating three hypotheses: transient wave amplitude/superposition, the tidal gate, and stationary waves, specifically western boundary currents.

In addition, the proposed work will fund continued development of the MDAD to the most recent release of Mars Color Imager observations of the Martian surface, and machine learning methods will be applied to the MDAD for trials of automated dust storm detection. Finally, statistical relationships between precursor activity and the development of major dust storms as identified in the MDAD will be examined for predictive power to determine if the conditions that promote the growth of large-scale dust storms can be anticipated simply based on the previous dust storm climatology.

Hannes Bernhardt/Arizona State University
Photogeologic study of Noachis Terra Crustal evolution and the effects of basin-forming events on early Mars
21-MDAP21_2-0047

We propose a comprehensive, photogeologic investigation of Noachis Terra, a ~4 million km2 large section of the cratered highlands between the Hellas and Argyre basins in the southern hemisphere of Mars. Noachis Terra is a key region to understand martian impact chronology, the geologic and environmental effects of large impact events on the planet's history, as well as crustal evolution. It is the namesake for the Noachian System, which forms the base of the martian stratigraphic system, with eastern Noachis Terra serving as the type area of the Middle Noachian series. The region is unique among the cratered highlands as it lies between the largest and third-largest, topographically well-defined impact basins on Mars, Hellas and Argyre Planitiae, but has not been intensely overprinted by volcanic or fluvial landforms. It therefore preserved the geomorphologic record by both basin-forming events, which emplaced poorly constrained amounts of secondary craters and ejecta on their surroundings and likely were decisive climate altering events. Noachis Terra is also instrumental for understanding crustal evolution as potentially felsic volcanic deposits, as well as floor-fractured craters have been noted in the area. However, despite its importance for Mars geochronology as well as crustal and climate evolution, only isolated landforms (e.g., tectonic features, dune fields) have been investigated in parts of Noachis Terra, and no comprehensive, systematic analysis has been conducted yet. This makes Noachis Terra one of the last physiographic macro-units that have not been subject to a dedicated study. As photogeologic mapping is the most comprehensive analytical approach based on remote-sensing data, we propose to prepare such a map at a scale of 1:2,500,000 in ArcMap/ArcGIS employing all modern datasets and state-of-the-art USGS-mapping techniques. The mapping will be based on THEMIS-IR daytime data and include the thorough identification, description, quantification (2-D & 3-D), as well as interpretation of all units and landforms visible on the employed datasets. Model ages of units will be derived from crater size-frequency distribution measurements and considered in conjunction with stratigraphic analyses. The map will serve as a basis to contextualize and discuss morphometric as well as hyperspectral analyses of specific landforms including infrared-dark plains, floor-fractured craters, and buried/unburied craters as well as quasi-circular depressions. The latter two will also enable improved, observation-based estimates of Hellas/Argyre ejecta depths and extents. These will be used to calculate the initially hot ejecta's subsurface warming effect on a possibly cold and icy" early Mars, thus potentially enabling transient habitability, widespread aqueous alteration, and possibly also temporary sterilization. The goal of this investigation is to develop an improved understanding of the geologic inventory and evolution of Noachis Terra and its adjacent regions, as well as their overall implications for the evolution of Mars' geology and habitability.

David Crown/Planetary Science Institute
Evolution of Martian Lava Flow Fields: Investigations of Pahoehoe-like Flow Morphologies in the Tharsis and Elysium Volcanic Provinces
21-MDAP21_2-0061

Volcanism is a dominant process forming the surfaces of the terrestrial planets. On Earth, basaltic lava flow fields often consist of diverse lava flow types; Hawaiian and other flow fields exhibit complex assemblages of a'a and pahoehoe flow textures. A'a flows have been widely used as analogues for planetary flows given their simpler shapes, larger dimensions, and well-developed central channels with lateral levees, as well as visibility in early spacecraft datasets. Because of this, there are significant knowledge gaps in our understanding of other lava flow processes and their roles in the evolution of Martian volcanic centers. Recent studies of Martian volcanoes have revealed flow features indicative of processes common to terrestrial pahoehoe lava flows. High-resolution imaging and topographic datasets can now be used to characterize diagnostic details of pahoehoe-like flow emplacement processes that occur in a number of locations with recent Martian volcanism.

We will study the morphologic varieties, topographic attributes, and spatial and temporal contexts of pahoehoe-like flows in a series of Martian lava flow fields in order to address the following: What do pahoehoe flow morphologies indicate about flow emplacement styles and rates? What do the morphologic diversity, spatial and temporal distributions, and volcanic settings of paheohoe-like flow features indicate about the evolution of Martian flow fields? and How do evolutionary patterns in flow field development compare at different sites?

The targeted study areas include: 1) southern Tharsis, including flow fields of the southwest rift apron of Arsia Mons, 2) eastern Tharsis, including rift apron flow fields adjacent to Pavonis and Ascraeus Montes, and 3) southern Elysium, particularly along the dichotomy boundary contact.

Task 1. Catalogue of Flow Morphologies: For each study area, we will compile a comprehensive catalog of p hoehoe-like flow features, characterize their volcanic settings, and identify possible source vents. In a subset of the larger population using CTX and HiRISE images and DTMs, we will outline flow margins, document textural/morphologic variations, measure longitudinal and cross-sectional profiles, and map surface planform distributary patterns.

Task 2. Spatial Distribution and Chronology: We will analyze spatial distributions of the different types of pahoehoe-like morphologies documented with respect to location in the flow field/volcanic province, relative to other volcanic features (including potential vents), and along any identified distributary pathways. We will select representative areas of pahoehoe-like flows in each flow field and derive absolute model age estimates from superposed craters, providing chronologic constraints on pahoehoe flow emplacement within the different regions of interest.

Task 3. Synthesis: Comparison of Martian Flow Fields: Robust interpretations of flow emplacement styles combined with documentation of their spatial and temporal distributions will constrain the volcanic evolution of lava flow fields in the Tharsis and Elysium provinces. This work will examine the context of and patterns in pahoehoe-like flow emplacement and document the overall significance of low effusion rate volcanism. This work will directly address knowledge gaps in our understanding of the development of Martian volcanic centers.

The proposed research is relevant to NASA MDAP goals regarding using spacecraft data to conduct investigations of planetary surface geology. The study addresses MDAP focus to enhance the scientific return from missions to Mars conducted by NASA and other space agencies." Results of this hypothesis-driven study, only appropriate for MDAP, will contribute to ongoing studies of Mars, with a focus on understanding the styles, magnitudes, and chronology of volcanism. This knowledge is fundamental to our understanding of the geologic evolution of Mars and the other terrestrial planets.

Ingrid Daubar/Brown University
Rockfalls on Mars - Indicators of Seismicity, Impacts, or Thermal Fatigue?
21-MDAP21_2-0069

Rockfalls are a dynamic erosional process that provides information about the endo- and exogenic activity and evolution of Mars. Rockfalls can be either indicators or sources of seismic/tectonic activity, can indicate current states of thermal stress and fatigue, can be related to meteoritic impacts of various scales, and are also measures of currently active mass wasting and slope modification processes. We propose to study present-day and geologically recent rockfalls over all of Mars, with special attention to proposed seismically active regions with nearby located seismic events, as well as date-constrained fresh impacts. We will apply cutting-edge machine learning methods to the large public database of high-resolution HiRISE images to maximize science return from these data. Our objectives are to 1) map and quantify the occurrence of rockfalls over the entire planet and 2) identify fresh rockfalls that have occurred over the past 15 years. This will enable us to identify locales and conditions that favor rockfalls; test hypotheses for triggering/driving mechanisms; and estimate the overall contribution of this erosional process to the geologic evolution of the martian surface.

We will use proven machine learning methods to search for rockfalls everywhere on Mars in HiRISE images and constrain their formation times where possible. Constrained rockfall events will be compared to published catalogs of marsquakes and known impacts to search for temporal matches. Comparisons will yield a relationship between types of events, and the minimum size and distance to trigger rockfalls.

The resulting catalog will also be used to explore aspects of the rockfalls and their environments. We will extract characteristics including boulder size and shape, thermophysical properties of rockfall locations, length of boulder track, source region geology, track deviation off steepest descent, rockfall kinematics, and the presence of volatiles/seasonal frosts. We will examine the global data for statistics of occurrences and trends in locations, temporal constraints, characteristics of the rockfalls themselves and their surroundings. Areas of known or suspected seismic activity, e.g. Cerberus Fossae, will be examined for enhanced rockfall spatial densities, magnitudes, and frequencies. This work will test hypotheses for the causes of rockfalls: are they triggered by seismic activity, recent impacts, volatile cycling, or thermal stresses in steep slopes?

This study would constrain an important form of mass wasting process across Mars in the geologically recent past, with implications for dynamic landscape evolution. We would quantify erosion rates due to rockfalls, constrain the minimum strength quake or impact event that results in downslope mass wasting, and explore the importance of solar insolation and seasonal frosts in driving landscape evolution on an atmospheric rocky body.

The MDAP program seeks to broaden scientific participation in the analysis of mission data sets". Our proposed use of multiple publicly available Mars mission datasets, including CTX and HiRISE on MRO and InSight for data analysis tasks falls within the scope of the MDAP program. This proposal would address several MEPAG science and exploration goals, primarily Goal III, Investigation A4.3: Characterize modern surface processes and their rates of change, and assess their origin" because we propose to characterize modern rockfalls on Mars, their timing, and controls on their formation. Goal IV is also addressed by our assessment of rockfall hazards and resulting risks to infrastructure and traversability, for example objective B4, Assess landing-site characteristics and environment related to safe operations and trafficability within the possible area to be accessed by elements of a human mission."

Colin Dundas/USGS Flagstaff
Measuring Production of New Secondary Craters on Mars
21-MDAP21_2-0030

Primary impact craters form from impacts of asteroids or comets on planetary surfaces. Secondary craters, in turn, form from material thrown out of primary craters, and can form in vast numbers, both within well-defined rays and scattered between them.

Secondary crater production and its importance in the total crater population is one of the major uncertainties in planetary crater chronology and age estimates. Because large numbers of secondaries can form in an instant, they violate one of the key assumptions inherent in those methods. This makes an understanding of secondary craters critically important for age-dating, particularly of young surfaces where impacts are sparse. These include some of the most interesting surfaces on Mars, such as Late Amazonian lava flows or those influenced by resurfacing during recent Ice Ages". However, secondaries are difficult to identify and isolate for study except when they occur in well-defined rays that exhibit distinctive morphologies like herringbone structure, whereas scattered" or background" secondaries are a much larger issue for crater chronology because they are easily mistaken for primaries.

One population of secondary impacts on Mars has distinctive characteristics that allow them to be definitively identified both within well-defined rays and scattered between them. These are the secondaries around extremely recent small primary craters, which create distinctive, ephemeral markings in dusty areas. Thus, for a brief interval it is possible to definitively identify scattered secondaries. This presents a unique opportunity for understanding secondary impacts and the projectiles that form them.

The proposed work will assess secondary impact production via two tasks involving analysis of HiRISE images. First, secondary impacts both inside and between rays will be evaluated for selected sites to determine the relative importance of rays and scattered secondaries, and to derive the size-frequency distribution of ejected material. Second, the target-property controls on secondary crater production will be assessed by comparing secondary formation in areas with greater and lesser dust cover, providing fundamental new information on the impact process and the formation of high-velocity distant ejecta. These tasks will provide new insights on the impact cratering process and the formation of secondary craters, setting the stage for new advances in crater chronology.

The objective of the Mars Data Analysis Program is to enhance the scientific return from missions to Mars. This study involves analysis of data from the MRO spacecraft and therefore falls within the scope of MDAP. This work addresses fundamental science questions identified by the Mars science community. Secondary craters are one of the major sources of uncertainty in crater chronology and age estimates throughout the Solar System, and impact cratering is perhaps the most universal geologic process in planetary science. While the proposed work is focused on Mars, the results will be valuable for understanding every world with a solid surface.

Colin Dundas/USGS Flagstaff
Investigation of Exposed Subsurface Ice on Mars
21-MDAP21_2-0093

The Martian cryosphere is one of the most dynamic and interesting parts of Amazonian Mars, at the interface between geomorphology and climate. It has been of wide scientific interest for many years and the focus of past and future instruments and missions. A key problem in cryospheric science is to identify, inventory, and characterize widespread buried ice. The distribution, depth, and purity of ice are fundamental parameters that provide information on when and how ice was deposited and modified.

Studying buried ice from orbit is challenging, but a new tool has recently emerged: natural exposures of ice from the subsurface. Two primary processes are known to cause exposures: new impact craters create temporary exposures that fade over a period of years, while localized erosion reveals cross-sections through thick ice at some locations. Studies of such features over the last decade have revealed important information about subsurface ice and provide near-ground-truth data for interpreting other remote sensing information.

The proposed work will pursue three tasks analyzing HiRISE images to maximize the information that can be derived from such exposures and test the possibility of another type of exposure. Task 1 will determine whether craters in the Medusae Fossae Formation expose any material with color properties similar to the ice exposed in mid-latitude craters. Task 2 will examine the temporal evolution of both crater and scarp exposures to test for evidence of spatial variations in dust content. Task 3 will test the possibility of a third class of natural ice exposure: shallow ice at high latitudes that may be exposed by the wind.

This is a focused, pilot study-scale project that will carry out straightforward tasks. Completion of these three tasks will provide valuable new results for the community goal of identifying, inventorying, and characterizing ice. We will provide a new test of the possible ice content in the equatorial Medusae Fossae Formation, determine the extent of spatial variability in ice content where seen in the craters and scarps, and examine evidence for an entirely new form of ice exposure with the potential to provide entirely new constraints on a very shallow ice table. These results will provide high-impact new evidence for the properties of Martian subsurface ice.

This work is entirely data analysis and will only examine Martian surface features, so it is relevant to the Mars Data Analysis Program. It addresses high-priority goals identified by the Mars science community.

Christopher Fowler/West Virginia University
The role of the solar wind interaction in driving upper ionospheric dynamics and energy deposition at Mars
21-MDAP21_2-0004

Mars' upper ionosphere acts as the interface between the impinging supersonic solar wind and the dense lower ionosphere. The collisionless nature of the upper ionosphere means that magnetic and electric fields are the primary facilitators of energy and momentum transfer from the solar wind to the charged particles of the upper ionosphere. Mars is constantly subject to a diverse range of upstream solar wind conditions that drive it's upper ionospheric structure. Previous works that have investigated this interaction have typically focused on the response of the macro properties of the Mars system (e.g. ion escape rates, large scale magnetospheric structure) to extreme space weather events, rather than the localized upper ionospheric structure to the full range of solar wind driving conditions.

Our study will provide the first comprehensive evaluation of how Mars' upper ionospheric density and temperature structure responds to the full range of the Mars-solar wind interaction conditions, allowing us to understand the physical processes that are commonly active as opposed to just the rare extreme cases.

Our proposed study will utilize in-situ plasma observations made by the Mars Atmosphere and Volatile EvolutioN (MAVEN) spacecraft. The ionospheric density and temperature structure, including it's variability, will be characterized, and its response to the full range of solar wind driving conditions will be evaluated in a statistical fashion.

Carefully chosen case studies will allow us to carry out detailed analysis of the MAVEN data in the context of the statistical results. Our case study analysis will include the identification and characterization of electromagnetic wave modes, wave-particle interactions, and their effects on ion distribution functions, in order to determine the physical mechanisms that drive the ionospheric response.

Our proposed study will address the following science questions:

1. How does the density and temperature structure of Mars' upper ionosphere respond to changes in the Mars-solar wind interaction?
2. How does the electromagnetic wave environment in Mars' upper ionosphere respond to changes in the Mars-solar wind interaction, and how does it influence the density and temperature structure?
3. What are the key physical processes that drive Mars' upper ionospheric responses to changes in the Mars-solar wind interaction?

Scott Guzewich/NASA Goddard Space Flight Center
Detecting Missing Dust Activity during Southern Polar Summer
21-MDAP21_2-0053

Science Goals and Objectives: Mars dust storms typically occur during the second half of the martian year during southern hemisphere spring and summer. Kass et al. [2016] noted that they usually occur in three distinct time periods, as defined by the thermal response they generate in the atmosphere. However, the second of these, the B" storms which occur near southern hemisphere summer solstice, are rarely seen in orbital imagery and are often indistinct and amorphous in measurements of atmospheric dust opacity, except during years with solstitial global dust storms (e.g., Mars Year 28). Indeed, the solstices are known to be periods of time that see a pause or reduction in dust storm activity around the planet [Guzewich et al., 2015; Battalio and Wang, 2021]. Our investigation would seek to reconcile these disparate data sets. Specifically, what are the spatial patterns of dust storms near southern hemisphere summer solstice? Is there greater time-of-day variability to such storms due to extended daylight at southern high latitudes in summer? Is the atmospheric thermal response seen near solstice consistent with the paucity of imaged dust storms?

Methodology: We will combine data from multiple instruments and missions to complete this work. Specifically, we will use orbital imagery from the Mars Orbiter Camera and Mars Color Imager (as represented in the Mars Dust Activity Database; Battalio and Wang [2021]) to examine the patterns of solstitial dust storms. We will use Thermal Emission Spectrometer and Mars Climate Sounder retrievals of temperature and dust extinction to examine the atmospheric thermal response to dust storms and the patterns of dust extinction in the atmosphere. In addition, we will use the MarsWRF general circulation model (GCM) to provide the full spatial and time-of-day coverage that we lack from observations. In conjunction, this will produce a complete picture of martian dust storms near southern summer solstice and how they influence the atmosphere.

Relevance to Mars Data Analysis Program: Our proposed research is relevant to the Mars Data Analysis program by analyzing data collected by and enhancing the science return of the Mars Global Surveyor and Mars Reconnaissance Orbiter missions and improving our understanding of open science questions related to Mars namely, patterns and processes of martian dust storms. All data required for this study has been publicly available for at least 30 days prior to this proposal submission. Our atmospheric modeling work is supportive and is necessary to analyze or interpret the data" and thus appropriate for a Mars Data Analysis project.

Edwin Kite/University Of Chicago
Mars Sedimentation in Space and Time
21-MDAP21_2-0050

A basic attribute of the Mars sedimentary rock record as viewed from orbit is that it is layered. Curiosity is now in a position to ground-truth these layers at a single site, making an analysis of their global properties timely. Perhaps surprisingly, there has never been a global survey of the most basic property of the light-toned layered sedimentary rock layers - their thickness - as a function of space (across Mars) and relative stratigraphic elevation (a proxy for relative time). We propose to carry out such a global survey of Mars Sedimentation in Space and Time. We will focus on the orbital facies for which layer thickness is best preserved   the "rhythmite", so-called because of the apparent regularity of layer thickness   and immediately underlying laterally-continuous sulfate materials. These are the globally distributed orbital facies corresponding to materials along Curiosity's future traverse. Motivated by the potential of the light-toned, layered sedimentary rocks to constrain past geologic processes on Mars, the broad goal of the proposed investigation is to constrain the origin of these rocks. The investigation has a single Objective: Test Hypotheses For The Origin of Light-Toned, Regularly Layered Sedimentary Rocks On Mars Via a Global Survey of Sedimentary Layer Thickness." The rhythmically-layered sedimentary rocks almost certainly required some liquid water to explain their induration/cementation, so they record an era when Mars had a more-habitable climate. Intriguingly, and in stark contrast to valley network formation which mostly ceased after the Early Hesperian, sedimentary rock formation extended into relatively recent times. However, our ability to read this record is currently limited, because the sediment source for these rocks is unknown. In one hypothesis, the rocks are primarily the indurated record of ash-falls from large explosive eruptions in Mars history, defining the largest pyroclastic deposits in the Solar System. This hypothesis predicts that the thickness of layers should decrease with distance from major volcanoes. Alternatively, the rocks may be primarily the indurated deposits of global wind-storms. In this case the spatial distribution of layer thickness should not be correlated with the location of volcanoes. Instead, because over Mars' geologic history wind-storms transported ample sediment to build up thick deposits, so that sediment supply should not be limiting, whereas in a cool climate meltwater availability for induration processes correlates with latitude, the layer thickness should be correlated with latitude. This is consistent with the observation that the thickest rhythmite deposits are close to the equator. Both liquid water availability and the ability of the atmosphere to transport sediment should generally decrease as Mars' atmospheric pressure declines. Therefore, a decrease in layer thickness with stratigraphic elevation would be consistent with the hypothesis that atmospheric pressure declined during the time span recorded by the light-toned layered sedimentary rocks. If no such trend exists, that would suggest no large net changes in the climate conditions needed for layer formation - including atmospheric pressure - during the (>>108 yr) time interval spanned by the light-toned layered sedimentary rocks. Additional hypotheses can also be tested using layer thickness measurements. The proposed measurements are enabled by the rapid recent increase in the number of HiRISE DTMs that are available for rhythmite facies rocks. We will analyze 57 existing HiRISE DTMs and construct 12 new DTMs. This will enable the hypothesis tests described in Table 1. The proposed work is a pure data analysis study, and involves no modeling. Nor will this investigation produce any geologic maps. Therefore it is not relevant to any other program. Because it will directly increase the science return from MRO, and (indirectly) from MSL, it is relevant to MDAP.

Armin Kleinboehl/Jet Propulsion Laboratory
Distribution and Composition of Mars Mesospheric Clouds from Mars Climate Sounder Observations
21-MDAP21_2-0035

Clouds on Mars are inherently tied to atmospheric conditions and processes both in their formation a favorable thermal structure, perturbations from dynamical phenomena, availability of volatiles and nucleation particles and in their subsequent feedback cooling through reflection of incoming solar radiation and warming by absorption of outgoing longwave radiation. Mars' atmosphere hosts both H2O-ice and CO2-ice clouds, which result from different formation mechanisms and impart different radiative effects that are sensitive to the particle sizes and opacities of the clouds. Mesospheric clouds are clouds observed above ~50 km altitude and have been identified across a range of wavelengths (ultraviolet, visible, and infrared) by several instruments from multiple spacecraft. They are seen in all seasons, at a variety of latitudes and longitudes, and several local times. A detailed characterization of the composition and particle sizes of different populations of mesospheric clouds is important for moving beyond mapping to understanding their formation and quantifying their impact on the atmosphere.
We propose to investigate the distribution and compositions of mesospheric cloud populations using the Mars Climate Sounder (MCS) onboard the Mars Reconnaissance Orbiter (MRO), which routinely observes mesospheric aerosol layers. Combining an extensive MCS cloud catalog with a simple radiative transfer model, we can determine climatologies of high-altitude aerosols in the Martian atmosphere. We plan to leverage the distinct spectral signatures of aerosol layers differences in radiance across MCS's channels to determine cloud compositions and use those compositions to improve our understanding of their formation and their connection to vertical transport and other dynamical phenomena in the atmosphere.

Our goal is to understand how the behavior of the Martian atmosphere the global circulation, regional and global dust storms, vertical transport, and dynamical phenomena influences the formation, distribution, and properties of mesospheric cloud and aerosol layers.
We aim to accomplish three objectives to progress toward this goal:
1. Determine the composition and particle sizes of identified discrete mesospheric clouds,
2. Characterize the distributions of H_2O-ice and CO_2-ice clouds and isolated dust layers in the mesosphere, their variability within and between key populations, and their relation to the environmental conditions in which they form,
3. Evaluate the effects of dust storms and gravity waves on mesospheric cloud formation.
We will use a radiative transfer model to fit radiances of identified mesospheric clouds in order to determine cloud compositions and particle sizes. We will characterize the spatial and temporal variability of cloud compositions and properties. We will draw connections between clouds and environmental conditions by comparing occurrence rates and properties conditions during and after global and regional dust storms as well as by investigating the spatial and temporal variability of clouds in relation to wave activity.
The proposed work is relevant to the Mars Data Analysis Program because it will enhance the scientific return from missions to Mars conducted by NASA and other space agencies" by directly analyzing data acquired by MCS on MRO.

Gareth Morgan/Planetary Science Institute
3-D Subsurface Imaging and Analysis of Glaciers and Lava Fields with SHARAD Data
21-MDAP21_2-0074

We propose to reveal and characterize new details of the internal structure and stratigraphy of Martian glaciers and lava fields by creating and analyzing 3-D volumes of Mars Reconnaissance Orbiter (MRO) Shallow Radar (SHARAD) sounding data. Questions we will address include: (1) Were there multiple phases of Martian glaciation? (2) Do all Martian glacial features have the same origin? and (3) How did the magnitude and style of volcanic eruptions vary over recent Martian History?

Long suspected to contain ice related to a prior climate state, so-called lobate debris aprons were shown to be ice-rich debris-covered glaciers because they allow strong SHARAD reflections at their bases. Elsewhere, young volcanic terrains exhibit some of the most complex subsurface structure detected by SHARAD outside of the polar caps. Multiple, overlapping radar reflectors at depth have been associated with stacked lava flows and sediments that represent the most recent sequence of eruptions to occur on Mars. However, the ability to fully characterize these features has been hampered by the effects of the associated high topographic relief and complex structures on radar signals. Standard processing of single-pass observations mis-positions sloping interfaces, including the surface itself and geologic contacts at depth, and this effect often leads to interference between off-nadir surface reflections (clutter) and subsurface reflections that obfuscates the latter. Using 3-D imaging routines applied collectively to many observations, clutter can be placed in its true position within the data volume, providing an improved visualization of interfaces, structures, and stratigraphic relationships at depth.

To produce the needed 3-D data volumes for this study, we will leverage previously developed methodologies for existing SHARAD volumes encompassing Planum Boreum and Planum Australe and apply them to four smaller mid-latitude study areas. We collect SHARAD echoes from many orbit passes into a uniform grid, co-registering them geographically and adjusting their delay times to a common datum, taking care to remove residual ionosphere-induced time delays using surface-clutter simulations produced from digital elevation models (DEMs). We then use 3-D processing methods to correct the scattered echoes from varying topography and structure and to enhance the final image. Upon completion of each 3-D radar volume, we will carry out a thorough analysis of the results to identify and map previously obfuscated and finer-scale subsurface structures within the glaciers and lava fields. The site-specific DEMs we will produce from MRO CTX images together with standard imagery from CTX and MRO HiRISE will be used in our analysis to provide context and allow more confidence in inferring the nature of subsurface layering and structures where they may intersect the surface.

Expected outcomes of this study include a better understanding of the emplacement history of glaciers and lava flows, with associated implications for the recent climate history and thermal evolution of Mars. Our proposed work will build on the published results of SHARAD 3D imaging studies developed under prior Mars Data Analysis Program (MDAP) grants. Since we seek to enhance the scientific return of the SHARAD instrument, our proposal directly addresses the primary objective of MDAP. In seeking to improve understanding of mid-latitude glaciers, which have been identified as a potential source of ice as a resource on future human missions, this proposal also has significance to NASA interests that extend beyond MDAP and the Science Mission Directorate.

Stefano Nerozzi/University Of Arizona

Reconstructing the stratigraphy, composition, and climate record of the north polar basal unit, Mars

21-MDAP21_2-0024

Science Goals and Objectives: The north polar basal unit (BU) is a sedimentary deposit of water ice and lithic fines buried within the Planum Boreum of Mars. Its large volume and volatile content make it one of the largest water ice reservoirs on the planet, likely the third largest after the two polar layered deposits. It lies stratigraphically between ancient (~3.45 Ga) and very young (<4 Ma) units, and thus provides the potential for a unique record of polar geologic processes and climate events spanning large portions of the Late Hesperian and Amazonian Periods. However, several key questions remain unanswered regarding the stratigraphic architecture, composition, and the nature and timing of events that are recorded in the strata of the BU. The objective of this proposal is to answer these questions in order to reconstruct the evolution of the BU through the Late Hesperian and Amazonian periods. The BU can be divided into two subunits, rup s and cavi, based on their stratigraphy and age. We will reveal the three-dimensional spatial distribution, stratigraphy, and composition of these units, and determine the timing of major accumulation and erosional events that shaped them. We delineate three sets of science questions that directly address several NASA research priorities delineated in MEPAG Science Goals II-B1, III-A1-3 (as solicited in ROSES C.9-4 3.2): (A) What are the extent and internal stratigraphic structures of the rup s and cavi units? (B) What is the rup s unit composed of? Is there any spatial variability in composition? (C) What was the accumulation and erosion history of the BU?

Methodology: Our proposed research work will take advantage of a rich and diverse set of Mars mission data, including subsurface radar sounding at multiple frequencies from two distinct radar sounders, high-resolution visible imagery, thermal imagery, and topography which will be analyzed in an integrated approach by three main research tasks to address each scientific question. Over 2,000 radar profiles acquired by the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) reveal the internal structure of the entire basal unit, including the contact between the rup s and cavi units, allowing us to determine their spatial extent and relative volumes. This extensive data set is complemented by a Shallow Radar (SHARAD) 3D data volume, which enables an even more detailed reconstruction of the morphology of the two units and the contact between them. Thanks to the MARSIS simultaneous operation on multiple frequencies, we can employ state of the art analytical techniques in multiple independent approaches to determine the fraction of water ice and nature of the lithic fines contained within the rup s unit, which are still largely unknown. Finally, we will test the hypothesis that the rup s unit accumulated as a dome of material growing towards lower latitudes and was then progressively eroded in the northward direction by examining the impact crater record on the adjacent plains in high-resolution visible images. Even in the case of a null result, this exercise will constrain the absolute ages of the rup s unit main accumulation and erosion events, thus providing insight to the timing of volatile and lithic transport on at least a regional scale during the Late Hesperian and Early and Middle Amazonian periods.

Relevance: This project directly addresses the MDAP objective of enhancing the scientific return from missions to Mars conducted by NASA and other space agencies. This study will analyze mission data from Mars Global Surveyor, Mars Odyssey, Mars Express, and Mars Reconnaissance Orbiter available to the public in the PDS at least 30 days prior to the proposal deadline.

Lujendra Ojha/Rutgers University, New Brunswick
Seasonal Slumps in the Equatorial Regions of Mars
21-MDAP21_2-0037

The contemporary surface of Mars experiences modifications by a variety of active geological processes such as dust devils, slope streaks, RSL, gullies, polar avalanches and others. Recently, a new type of surface feature has been observed on the slopes of the equatorial regions of Mars. Dark topographic slumps several meters wide, tens of meters in length, and up to a meter in depth have been recently observed on the slopes of Juventae Chasma (JC), Valles Marineris (VM), Mars. These slumps usually originate near the terminal points of recurring slope lineae (RSL), as viewed in High Resolution Imaging Science Experiment (HiRISE) images. Near their initiation points, the slumps have topographic depressions due to the removal of materials; near their lowermost reaches, new materials are deposited in lobes. Over the course of seven Mars years, numerous active slumps have been observed, all of which formed in or near the same season (areocentric longitude: Ls 0° 120°). The objective of the proposal is to investigate further the geographical distribution, morphology, and seasonality of the topographic slumps in the equatorial region of Mars. The results from this endeavor will allow us to ascertain better the formation mechanism of these intriguing surface features on Mars. Further, a detailed study of these features may also help us establish if RSL play a role in creating contemporary slumps. Specifically, we seek to answer the following research questions about topographic slumps:

" Are topographic slumps common on steep slopes of the equatorial region of Mars? Or are they only found on RSL-hosting slopes?
" Do topographic slumps elsewhere also exhibit seasonal dependence as observed in JC (i.e., Ls 0° 120°)?
" What are the various surface conditions necessary for the formation of topographic slumps?
" How fast does the low albedo of slumps fade, and does this rate compare similarly with other processes (e.g., dust devil tracks, new impact crater ejecta)?
Answering the above research questions will help us better understand the processes responsible for the formation of topographic slumps. In particular, the stated objectives will allow us to understand if slumps are a new class of seasonal features on Mars (e.g., spiders, polar avalanche) or if these are stochastic, gravity-driven features that are occasionally observed on steep equatorial slopes with the most repeat high-resolution images. Furthermore, if slumps are exclusively found on RSL hosting slopes, then that may also suggest that RSL are actively modifying the contemporary surface of Mars.

This proposal is relevant to the objectives of the MDAP program as stated in ROSES 2021, C.9, Section 1, Scope of Program. It will enhance the scientific return from missions to Mars" by allowing analyses of multiple publicly available martian datasets. It will broaden scientific participation in the analysis of mission data sets" by supporting scientists who would otherwise not be funded to do these analyses. The research to be undertaken will improve our understanding of open science questions", specifically: providing a deeper understanding of the dynamic nature of the martian surface and atmosphere.

Tim Parker/Jet Propulsion Laboratory
Origin, Timing, and Fate of a Mars Ocean

21-MDAP21_2-0073

For decades it has been recognized that there are geomorphic and chemical signatures suggestive of a past ocean in the northern plains of Mars. A key part of present understanding is the geomorphic evidence of possible paleo-shorelines that persisted for long periods of time and at heights of hundreds to thousands of meters above the elevation of the northern plains. This proposal will investigate the formation of the ocean, its evolution, timing, and ultimate fate. It begins with a global map of potential shorelines, on which more than a dozen distinct levels have been identified at elevations from -4000 meters to +1200 meters. These proposed shorelines, are typically expressed as subtle erosional terraces often associated with over-lying mantle deposits with lobate margins, or as broad, degraded erosional terraces evident primarily in the regional topography. The global CTX image mosaic and global HRSC/MOLA DEM will be used to improve the XYZ placement of these features with respect to the geoid. The global data provide consistent image resolution and topographic precision that are quickly accessible for both detailed regional and overall global evaluation of the features thought to be shorelines. This approach will enable better estimates of water volumes contained within each level than are currently possible. To accomplish this, the XYZ placement of the mapped levels will be used to infer the once-geopotential surfaces indicated by them and thus include tectonic and isostatic effects that could affect volume estimates for each level. The general history of emplacement and de-leveling over time of proposed paleoshorelines around the planetary dichotomy boundary will be deduced by using superposition relationships to mapped geologic units for which abundant crater-age determinations have been published in the literature over the past 40 years. This is a three-year investigation with 3 tasks: Task 1 will be to evaluate the placement of mapped shapefiles and extend identification of the higher, less well-preserved levels where possible. Task 2 will be to measure global trends in elevation of the levels and water volumes in cubic kilometers and Global Equivalent Layer values, to compare with published model predictions of volatile inventory relative to planetary accretion, outgassing, and Late Heavy Bombardment. This task will make relative age determinations of the proposed shorelines based on superposition relationships to regional geologic surfaces for which ages have been assigned in the published literature). Task 3 will develop and apply geophysical models of surface response to large sediment and water loads. This task will include formulation of hypotheses to explain deviations from equipotential surfaces measured in Task 2 that might indicate isostatic and tectonic de-leveling of the proposed shorelines over time.

The objectives of this proposed research are consistent and relevant to the goals of NASA's Mars Data Analysis Program under the following research topics: (1) use of reduced, calibrated, publicly available data from planetary missions (MGS, MRO, and Mars Express) to enhance scientific return from past and current Mars missions 2) photogeologic analysis and geologic interpretation of contacts and surfaces related to proposed shorelines for which there is now abundant new image and topography data.

Reid Parsons/Fitchburg State University

Using glacial moraine sequences on Arsia and Pavonis Mons to constrain recent climate change events on Mars by employing an ice sheet model
21-MDAP21_2-0039

Background: The fan-shaped deposits (FSDs) on the flanks of the prominent Tharsis volcanoes (Arsia, Pavonis, and Ascraeus Mons) are among the largest surface features associated with recent climate change on Mars. The striking ridge sequences found within the Arsia and Pavonis FSDs are glacially deposited moraines representing the margin of a former ice sheet. Thus, the ridges provide a history of ice margin locations and record the growth and decay of equatorial ice sheets as the climate changed due to variations in obliquity. Superposed on the ridges is a young, discontinuous smooth unit containing remnant ice buried below a debris layer at both the Arsia and Pavonis FSDs. Global climate model simulations results show ice accumulating on the Tharsis volcanoes at an obliquity of 45 degrees due to equatorial transport of water vapor sourced from the polar caps. Periods of obliquity exceeding 45 degrees have occurred within the past 10 Myrs - suggesting an active ice sheet deposited a portion of these FSDs in the very recent past.

Science Objectives/Goals: The overarching goal of this work is to place constraints on the Amazonian obliquity history using the smooth units and ridge sequences found within the Arsia and Pavonis FSDs. Because the ridges record the location of the ice sheet margin, they provide valuable information about the rates and extent of ice accumulation and ablation which, together with ice flow, dictate the location of the ice margin. Objective1: Measure ridge morphology and determine the relative chronology among ridge sequences and smooth units in order to reconstruct the episodic growth and decay of the former ice sheets at the Arsia and Pavonis FSDs. Objective2: Combine geomorphic mapping with numerical ice sheet simulations to better constrain the Amazonian climate history recorded in these important deposits.

Methodology: Using a combination of CTX and HiRISE images, stereo DTMs as well as HRSC images, we aim to determine superposition relationships for locations in the Arsia and Pavonis FSDs where ridge sequences intersect. Additionally, a targeted survey of ridges in the Arsia and Pavonis FSD at CTX resolution will provide a dataset of ridge locations from which fluctuations in ridge spacing can be determined and correlated between the Arsia and Pavonis deposits. Including superposed smooth units in this analysis, recent glacial maximums (RGMs) can be determined using relative dating principles. This dataset will be supplemented with ridge cross sectional measurements from HiRISE and CTX stereo DTMs.

The open-source Parallel Ice Sheet Model (PISM) will simulate the accumulation and flow of ice under martian gravity and temperature using gridded MOLA topography input and assumptions regarding the obliquity-ice mass balance relationship over the last 25 Myr. The mass-balance inputs will be fine-tuned by determining which ice mass balance assumptions produce an ice sheet margin that best coincides with the RGMs. These results will then be applied to a set of unconstrained obliquity scenarios extending back to

250 Myr to determine which obliquity scenario best explains the number and location of the observed ridges.

Relevance: This work addresses the formation and evolution of ice sheets formed from obliquity-driven climate change on Mars and will transform our understanding of the relationship between obliquity and atmospheric water ice transport. The 2020 MEPAG has highlighted this science objective in Goal 2, Sub-Objective B2 which addresses the analysis of features at low- and mid-latitudes to extract a record of recent climate. This work also analyzes HiRISE and CTX images collected by MRO, HRSC data from Mars Express, and uses topography data from MGS to model the formation of FSD ridges - fulfilling the objectives of the MDAP.

Alain Plattner/University Of Alabama, Tuscaloosa
Geophysical Evolution of the Martian Crust from Magnetic Source Depth Analysis of MAVEN Data
21-MDAP21_2-0010

The Martian crustal magnetic field, first detected over two decades ago by NASA's Mars Global Surveyor (MGS) satellite, has provided insights into and challenges in understanding the geophysical evolution of Mars. Like topography, the magnetic field intensity exhibits a roughly hemispheric dichotomy with strong crustal magnetic fields over the rugged southern highlands, and weak fields over the northern lowlands. Magnetic data collected by NASA's Mars Atmosphere and Volatile EvolutioN (MAVEN) satellite since 2014, together with recent methodological advancements, allow us to now tackle two fundamental, outstanding questions about Mars' crustal structure and history.

Research Question 1 (RQ 1): Could the strong magnetic signals in the Terra Cimmeria and Sirenum region be a consequence of serpentinization that could have provided substantial amounts of molecular hydrogen to potential early life in the crust of Mars?

Research Question 2 (RQ 2): What geologic processes shaped the weak crustal magnetic fields in the northern hemisphere? More precisely: What are the magnetic source depths of the various magnetic signals in and around the Northern Lowlands?

Answering the RQ requires tight constraints on the depths of magnetic sources. Source depths obtained from recent global crustal magnetic field models are a step forward in this direction, but have too large an uncertainty (sometimes extending from above the planet into the mantle) to address these key issues. This is a consequence of the use of global models to calculate local source depths by examining the relative power in different spatial wavelengths of the magnetic field. Global models that fit weak and strong magnetic fields simultaneously can introduce ringing into the resulting model, which then biases source depth calculations. Smoothness constraints may additionally compromise source depth estimations by affecting different spatial wavelengths differently.

We propose a different approach. For each investigation location we will calculate local crustal magnetic field models for various choices of smoothness constraints and random data subsampling. From these local models, we will calculate source depths and use the variation in outcomes to explore uncertainties in source depths. We demonstrate that the proposed approach can yield source depths with an uncertainty sufficient to address the RQ.

RQ 1 is relevant as it pertains to MEPAG-2020 GOAL I, Objective A, Sub-Objective A.2: "Investigate the nature and duration of habitability near the surface and in the deep subsurface." MEPAG-2020 also notes: "... the subsurface should be considered an exciting new frontier for Mars exploration, and a particularly promising target environment to address the objectives presented in Goal I."

RQ 2 is relevant as it pertains to MEPAG-2020 GOAL III, Objective A, Sub-Objective A4: "Determine the nature and timing of construction and modification of the crust." Determining the spatial variation of the magnetic source depths will provide a new perspective of the geologic processes of the Northern Lowlands.

ROSES MDAP is the most appropriate program element for this proposal, because the proposed research questions will be solved using MAVEN data. This proposal is focused on data analysis and no substantial new methodological developments will be carried out.

Elizabeth Rampe/NASA Johnson Space Center
Expanding the Catalogue of Trace Elements in Gale Crater Rocks and Soils to Enhance Interpretations of Geochemical Processes on Mars
21-MDAP21_2-0032

The Mars Science Laboratory Alpha Particle X-ray Spectrometer (MSL-APXS) has conducted more than 1,100 measurements of rocks and soils, and that dataset contains trace element information that can improve our understanding of the geologic record of Mars. The 16 major, minor, and trace elements that the MSL-APXS has quantified and released to the Planetary Data System (PDS) have informed interpretations of the geologic history of Gale crater, but many details are poorly constrained and important questions are unanswered. This is partly because major and minor elements (>0.1%) can occur in multiple phases and correlate with multiple elements, thus obscuring geochemical processes. In terrestrial laboratories, this ambiguity can be overcome by analyzing trace elements that are linked to specific geochemical processes. However, most trace elements are often below the APXS detection limits for individual measurements. The APXS limit of detection is primarily affected by statistics and resolution. Resolution is largely driven by temperature. Statistical effects include proximity to the sample, X-ray excitation source decay, and integration length. The integration length for a single target is typically limited to less than 8 hours to keep the MSL mission moving forward; longer integration times would result in lower detection limits. This project proposes an approach that improves on this time constraint through spectral compositing, which permits the realization of lower quantification limits of trace elements within MSL-APXS data.

The overarching goal of this proposal is to conduct an analysis of the MSL-APXS dataset to develop an extended catalogue of trace element concentrations and apply testable hypotheses that enhance the understanding of the geologic processes recorded in Gale crater. The overarching goal will be accomplished by pursuing three objectives:
Objective 1: Classify APXS targets and define compositional groups. Publicly available MSL data will be analyzed to define groups of APXS targets that are related by similar elemental composition and geologic context. Groups will be defined quantitatively such that the elemental composition of multiple APXS targets can be analyzed as composites.
Objective 2: Create and analyze composite spectra. Using the groups of APXS targets defined by Objective 1, composite APXS spectra with significantly longer effective integration times will be created and analyzed to determine trace element concentrations with improved detection limits. Elements of interest include V, Co, Cu, Ga, Ge, As, Se, Rb, Sr, and Pb.
Objective 3: Evaluate new trace element results and apply testable hypotheses. The trace element results will be analyzed and evaluated within the geologic context provided by the full Curiosity rover science payload to test hypotheses about the geologic history of Gale crater.

Expected significance: The proposed work is anticipated to result in an expanded catalogue of trace elements in Gale crater. Trace elements on the martian surface have been used to infer the characteristics of sediment sources, identify likely hydrothermal processes, and provide evidence of fluid interaction with rocks, with constraints on the geochemical characteristics of the fluids. Thus, an expanded catalogue of trace elements has the potential to provide additional information on the composition and geologic history of Gale crater, enhancing the science objectives of the MSL mission.

Emilie Royer/Planetary Science Institute
Harmonic Analysis of the Martian
Nitric Oxide Nightglow
21-MDAP21_2-0041

Since 2014, the Mars Atmosphere and Volatile Evolution (MAVEN) spacecraft has continuously monitored the Nitric Oxide (NO) nightglow at Mars, thanks to the capabilities of the Imaging Ultraviolet Spectrograph (IUVS) instrument. The extensive spatial and temporal coverage acquired by IUVS allowed for the first detection of wave patterns in the NO nightglow. At the equatorial region, a wave-3 structure has been identified, as well as a wave-2 structure in the northern hemisphere for latitudes poleward of 60º. The interplay of these two wave components with latitude, local time, season, and altitude are not yet well understood.
We propose here to further the investigation of the wave-3 and wave-2 components discovered by IUVS by performing a comprehensive and systematic harmonic analysis that includes uncertainties for the components as allowed by the data. The information on

the amplitude and phase of the observed waves obtained by such analysis will help to identify the waves' origin and better define their characteristics. Furthermore, by providing information on the nightside of the planet in the 60-80 km altitude range, we will complete a gap in the current knowledge of non-migrating tides in the Martian atmosphere. To strengthen the interpretation of the MAVEN-IUVS data, we will incorporate and cross-correlate results from the Mars Reconnaissance Orbiter (MRO) Mars Climate Sounder (MCS) mesospheric temperature dataset as part of this study, as a harmonic analysis technique has already been successfully applied to this dataset and the MCS data covers similar altitude, latitude, longitude and solar local time ranges as the IUVS dataset. We will consider diurnal, semi-diurnal, non-migrating or migrating waves or a combination of them as origin of the observed patterns. The NO nightglow in the upper atmosphere of Mars acts as a tracer of the descending branch of sub-solar/anti-solar circulation. Thus, results from the NO nightglow behavior provided by our harmonic analysis will help place constrains on the atmospheric dynamics and transport to help improve outputs from Mars CGMs.
This project seeks to enhance the scientific return from missions to Mars as stated in the ROSE 2021 C.9 Mars Data Analysis document. This scientific investigation will seek to improve atmospheric models that further the understanding and forecasting of Mars atmospheric conditions.

Cassini Data Analysis Program
Abstracts of Selected Proposals
(NNH21ZDA001N-CDAP)

Below are the abstracts of proposals selected for funding for CDAP. Principal Investigator (PI) name, institution, and proposal title are also included. 38 Step-2 proposals were received in response to this opportunity. On October 8, 2021, 15 proposals were selected for funding.

Jason Barnes/University of Idaho, Moscow
Titan Roughness and Grain Properties from Surface Phase Functions

We propose to constrain the physical and chemical properties of Titan's surface layer by measuring the surface reflectance phase function from Cassini/VIMS data. Previous studies have assumed a Lambertian surface phase function -- a fine first step, but all observed planetary surfaces are decidedly non-Lambertian. To aid in our evaluations, we will use our new 3D Monte Carlo radiative transfer program SRTC++. Because it allows for fully spherical geometries, SRTC++ can impose arbitrarily complex surface reflectance phase functions when simulating observations. Four tasks comprise our proposed work: (Task 1) Forward modeling of candidate surface phase functions through Titan's atmosphere, (Task 2) characterization of lakebed evaporites by evaluating the phase function of 5-micron-bright terrain, (Task 3) constraining the properties of low lying terrains using the phase function of dark-blue and dark-brown terrain, and (Task 4) constraining the properties of Titan's uplands from the phase function of equatorial bright and Xanadu terrain.

Peter Delamere/University of Alaska, Fairbanks
Is Saturn's magnetosphere Jupiter-like, Earth-like, or Saturn-like?

The goals and objectives of the proposed work

Giant planet magnetospheres, due to their size, multi-body nature, and rotational dynamics are some of the most complicated and least understood magnetospheres in the solar system. Recent simulation studies have demonstrated that much of Jupiter's polar region contains closed flux. This leads to dramatic auroral emissions that bear little resemblance to Earth’s aurorally dark polar cap. It is been debated that Saturn is an intermediate between Earth and Jupiter. On one hand, Saturn's rapid rotation and internal source of plasma would suggest a Jupiter-like magnetospheric configuration. Yet, the polar region tends to be aurorally dark like that of Earth. This proposal seeks to understand the magnetic topology of Saturn's magnetosphere with particular focus on tail dynamics and the polar region. Understanding the magnetic topology is critical for understanding the source mechanisms for the observed variability of plasma conditions (i.e., order of magnitude variations in plasma density and temperature) in the dawn-sector magnetosphere. Specifically, this proposal seeks to address the following questions:

" On average, how much of the magnetic flux threading Saturn's polar region is connected with the interplanetary magnetic field (open flux)?
" How does the open flux content vary with solar wind conditions (e.g., dynamic pressure)?
" What are the processes in the magnetotail to give rise to order-of-magnitude variability of plasma conditions in the dawn-sector magnetodisc?

Methodology

To address these questions we will: (1) Investigate and quantify departures from long term averages in terms of thermal plasma properties (density, temperature, entropy, and flows derived from the CAPS instrument) and magnetic field configurations (MAG); (2) Catalogue the frequency and properties of suspected tail-initiated transport events; (3) Compare select transport events with the energetic particle data from the Low-Energy Magnetospheric Measurement System (LEMMS) and Charge-Energy-Mass-Spectrometer (CHEMS) instruments; (4) Conduct high resolution three-dimensional, multi-fluid MHD simulations of Saturn's magnetosphere using the Grid Agnostic MHD for Extended Research Applications (GAMERA) model; (5) Conduct test particle simulations to understand the transport mechanisms from the nightside to the dayside; (6) Compare simulation results with Cassini data from high latitude regions (e.g., >30 deg) to better understand the possible signatures of open and closed magnetic flux.

Relevance to the Cassini Data Analysis program

The objective of the Cassini Data Analysis Program (CDAP) is to enhance the scientific return of the Cassini mission by broadening the scientific participation in the analysis and interpretation of data returned by this mission (App. C.10, ROSES21). Our proposed methodology combines 1) data analysis tasks (analysis of CAPS, LEMMS, CHEMS, and MAG data) and 2) non-data analysis tasks that are necessary to analyze or interpret the data (modeling and theory of transport). We will directly address the following science topics defined in the 2014-2033 Heliophysics Science and Technology Roadmap: (F1) Understand magnetic reconnection (magnetodisc/magnetotail reconnection and the solar wind interaction), (F2) Understand the plasma processes that accelerate and transport particles (magnetodisc heating and auroral processes), (F5) Understand the role of turbulence and waves in the transport of mass, momentum, and energy (Saturn is inherently turbulent). Science closure will lead to transformative advances in understanding of the giant planet magnetospheres. In addition, the proposed study is highly relevant to current and future NASA missions (e.g. Cluster, THEMIS, MMS, Pioneers 10 and 11, Voyagers, Galileo, and Juno.)

Matthew Fillingim/University of California, Berkeley
Determining Horizontal Ionospheric Currents and their Variability at Titan

Lacking a global internal magnetic field but possessing an ionizable atmosphere, Titan is an example of a Solar System object with an induced magnetosphere. Motions of the incident plasma (typically Saturn's magnetospheric plasma and magnetic field), induce currents in the ionosphere of Titan that in turn generate ionospheric magnetic fields that deflect the incident plasma and shield out the external magnetic field.

The main objective of the proposed work is to determine horizontal currents flowing in the ionosphere of Titan. This will be done by measuring perturbations in the magnetic field as observed by Cassini, and then calculating the current densities necessary to create the observed perturbations. This will be done for individual spacecraft flybys using data from the magnetometer instrument (MAG) when the spacecraft passed through the bulk of the ionosphere measuring local changes in the magnetic field due to local ionospheric currents. We will measure how the currents change as a result of changes in the incident plasma and external magnetic field (as measured by Cassini just before or after passing through the ionosphere). Additionally, we will use a high resolution hybrid model to simulate the magnetic field and currents that are induced in the ionosphere as a result of the incident plasma and magnetic field. These simulations will provide a global context for the local measurements.

The overarching goal of this work is to understand the structure and variability of the ionospheric currents that contribute to the development of the induced magnetosphere of Titan. The results of this work will aid our understanding of how the induced magnetosphere of Titan is formed and how it changes due to variations in the external drivers.

Alexander Hayes, Cornell. Science-PI Valerio Poggiali
Titan Surface Properties from Cassini RSS Bistatic Observations

Between March 2006 and November 2016, the Cassini spacecraft conducted 13 Radio Science bistatic scattering observations of Titan's surface. These observations contain novel insights into the physical properties of Titan's solid and liquid surfaces. To date, however, not a single refereed journal paper has reported results from the Cassini Bistatic scattering dataset. At present, only three AGU abstracts with few details (Marouf et al., 2006; 2008, 2014) document the totality of the significant effort that has been made to design and carry out these complex experiments. Herein, we request support to analyze all 13 of the Cassini Bistatic observations. While these observations are challenging to process, they can be directly related to surface dielectric constant (through the circular polarization ratio, or CPR) and roughness (via observed Doppler spread). Combining these measurements with the context provided by existing Cassini data (from RADAR, VIMS and ISS) will produce new and important constraints on the composition and surface texture of Titan's lakes, seas, and solid surface. Bistatic scattering refers to any experiment where microwave signals from one source are reflected from a target surface and received at another location. This technique enables diverse scattering geometries (e.g., Brewster's angle) and measurements (e.g., CPRs) optimized to directly derive target surface dielectric constant and roughness (e.g., Fjeldbo, 1964; Simpson, 1993). As six of Cassini's 13 bistatic scattering observations cross liquid hydrocarbon lakes and seas, this dataset offers a unique opportunity to validate and refine the liquid compositions inferred from dielectric properties derived by Cassini's Ku-Band RADAR altimetry-mode observations. The Bistatic dataset may also include depth measurements in the form of sea floor returns and multi-wavelength surface roughness measurements that can be used to investigate the cause of sea surface variability (e.g., waves vs. surfactants).

Robert Johnson, University of Virginia. Science-PI Adam Woodson
Plasma distributions along Titan's orbit and the production and evolution of the moon's nitrogen torus

It has long been proposed that Titan's atmosphere is strongly influenced by its interaction with Saturn's magnetospheric plasma. Although understanding this interaction was a primary goal of the Cassini mission, a comprehensive analysis of plasma distributions in Titan's interaction region and along the moon's orbit has yet to be performed. Prior to the Cassini mission, nitrogen liberated from Titan's atmosphere was expected to permeate the magnetosphere, and modeling suggested a substantial neutral torus at Titan's orbit as well as extensive inward transport and ionization. However, in situ observations of this nitrogen have been elusive, and it remains unclear why the torus was not more readily observed at predicted levels. A comprehensive analysis of the plasma data in this context is therefore imperative for understanding Titan's place in the magnetosphere.

The Cassini Plasma Spectrometer (CAPS) transformed our understanding of Saturn's magnetosphere throughout its nine operational years in orbit. However, the instrument's novelty and complexity have frustrated comprehensive analysis of the data, particularly when it comes to Titan. For example, the broad mass and energy ranges of the CAPS Ion Mass Spectrometer (IMS) demanded extensive calibration measurements and simulations that were never fully realized. These missing calibrations, in addition to various operational quirks and arcane technical details, have resulted in a large data set that is highly underutilized in the investigation of Titan's magnetospheric interaction.

A number of studies have surveyed Saturn's thermal plasma, which we now know to comprise primarily H2+ from Saturn, Titan and other objects; H+ and He++ from the solar wind; and water-group ions (e.g., O+, OH+, H2O+, H3O+) from Enceladus and the rings. But these studies have largely ignored Titan's interaction region. IMS spectra acquired near Titan demonstrate that, in addition to the thermal plasma composition, the interaction region is populated by a mixture of heavy hydrocarbon and nitrogen-bearing ions out to ~6 Titan radii or more. Few of these spectra have been analyzed thoroughly, and their implications for atmospheric loss and the erosion of Titan's neutral torus have not been sufficiently explored.

Therefore, the primary goals of the proposed work are the following: 1) perform instrument simulations using an existing SIMION model of the IMS to calculate detection efficiencies for a number of uncalibrated molecular ions relevant to Titan's interaction region; 2) use the calculated efficiencies to compile localized plasma (ion, electron) phase space densities (PSDs) from data acquired by CAPS/IMS and the CAPS Electron Spectrometer (ELS), as well as the Magnetospheric Imaging Instrument's Low-Energy Magnetospheric Measurements System (MIMI/LEMMS); and 3) incorporate the new, data-derived plasma PSDs into an existing torus evolution model to better quantify the spatial and temporal transport and ionization of Titan's lost nitrogen in the outer magnetosphere. The proposed work is highly relevant to the Cassini Data Analysis Program, as it will make use of several Cassini data sets to explore the fate of Titan's escaped nitrogen and provide insight into the dearth of direct measurements of the moon's long-anticipated but elusive neutral torus. The proposed work will also yield high-level data products in the form of plasma PSDs to facilitate scientific participation in the analysis of mission data relevant to Titan. For example, the distributions will provide constraints for other Titan models and for interpretation of observations by other Cassini instruments such as the Ion and Neutral Mass Spectrometer (INMS) and the Radio and Plasma Wave Science instrument.

Michelle Kirchoff/Southwest Research Institute
Tectonic Erasure of Impact Craters: New Constraints from Observations and Modeling of Enceladus' Craters

Background: Erasure of craters occurs on multiple outer solar system satellites. However, on most of these satellites all that remains is a surface (often highly tectonized) with low crater density, and the actual processes (e.g., cryovolcanic and/or tectonic) that led to erasure remains unclear. Fortunately, Enceladus displays craters at multiple stages of the tectonic erasure process, including almost pristine craters, craters additionally modified by viscous relaxation, and craters that are almost completely erased, but still visible. Therefore, analysis of Enceledus' modified craters, at varying stages, can provide new and vital constraints for geophysical numerical models of tectonic erasure and Enceladus geophysical evolution. Previous work on Ganymede lead to the hypothesis that tectonic erasure of craters involves a combination of viscous relaxation and lithospheric extension. Unfortunately, due to limited high-resolution imaging of Ganymede, the observational constraints needed to test this hypothesis were lacking. Cassini data, in contrast, provides a high-quality data set to test this hypothesis. Here we plan to combine observations and finite element models of tectonic erasure of craters on Enceladus to gain a better understanding of crater erasure on icy satellites and constrain Enceladus' evolution.

Science Goals and Objectives: The science objectives we propose are the steps needed to achieve our overall goal of gaining a better understanding of tectonic erasure of craters and the surface evolution of Enceladus. We plan to: 1) Analyze the morphology/morphometry of craters in various states of erasure on Enceladus. 2) Examine distributions of craters in various states of erasure to determine relative timing of events and provide additional constraints on erasure processes. 3) Summarize these analyses into new constraints for the finite element models. 4) Run finite element simulations through the complete process of tectonic erasure of craters to gain new insights into the process.

Summary of Methodology: The first step will be to select craters in various states of tectonic erasure and relaxation from an Enceladus crater database, which includes this information. The selection process will primarily consider coverage by high to moderate resolution Cassini ISS images and secondarily by high-resolution Cassini ISS stereo pairs. Then, we will perform crater measurements including size, relative degradation state, the quantity of cross-cutting tectonics, and qualitatively how tectonics modify a crater. In addition, for some craters we will generate high resolution topography from stereo pairs using Ames Stereo Pipeline and then compile 3-D measurements, such as depth of the craters. We will also examine both superposition and spatial distributions of craters to determine timing and other additional constraints. All measurements will then be combined to put together an evolutionary picture of how craters are erased and develop the constraints for the finite element models. Finite element modeling (Tekton v2.3) of viscous relaxation and extension will then be used to forward-model the observed crater forms and deformation types to understand strain magnitudes and thermal conditions necessary to completely erase craters.

Relevance to CDAP: The proposed work will enhance the scientific return of the Cassini mission by using ISS images of Enceladus to yield new information on the tectonic erasure of craters, a process that is found on several outer solar system satellites. We will be providing new information on how icy satellites are resurfaced and evolve. We also will produce high-resolution topography of some tectonically modified craters on Enceladus that will be archived on the PDS.

Tommi Koskinen/University of Arizona
The changing seasons of Saturn's upper atmosphere viewed in the ultraviolet

During its 13 years in orbit, Cassini obtained unprecedented observations of Saturn's upper atmosphere. The first in-situ observations of the equatorial thermosphere and ionosphere during the Grand Finale tour revealed a surprisingly large, temporally variable influx of material from the rings. Stellar occultations from the Ultraviolet Imaging Spectrograph (UVIS) were used to monitor the upper atmosphere intermittently throughout the mission. During the Grand Finale, they provided a snapshot of the upper atmosphere from pole to pole that constrains photochemistry, circulation and redistribution of energy. In addition, UVIS obtained an extensive archive of ultraviolet images of Saturn's dayglow, aurora and rings. While the aurora have been studied in detail before, dayglow and ring images have received limited attention to date and remain a source of vital new discoveries. We propose to reduce and analyze these observations to further characterize the upper atmosphere and its interaction with the rings.

The detected emissions, observed simultaneously in the EUV (56.3-118.2 nm) and FUV (115-191.2 nm) channels of the instrument, include the He 58.4 nm line, H2 electronic bands, the H Lyman-a line, and scattered sunlight at wavelengths longer than 150 nm. The images and limb scans cover several latitudes and longitudes at the same time, allowing us to probe spatial and temporal trends in the upper atmosphere throughout the mission. Extended system scans at Lyman-a probe atomic hydrogen in the ring atmosphere. The brightness of the ring atmosphere changes over time, due to changes in the atomic hydrogen content, and the images provide a means to track these changes and a possible way to constrain ring-atmosphere interactions. Since the ring emissions are optically thin, we can easily forward model the distribution of atomic hydrogen and fit it to match each image.

Recent work produced a robust calibration and confirmed that Saturn's Lyman-a dayglow is mostly produced by resonant scattering of solar emission by atomic hydrogen above the homopause, below which methane absorbs Lyman-a radiation. The H2 emissions, on the other hand, are produced by a combination of photoelectron excitation and solar fluorescence. The latter component is particularly sensitive to the abundance of H2 in the thermosphere, and the emissions are also absorbed by methane and more complex hydrocarbons near the homopause. With the aid of a radiative transfer model developed for giant planet upper atmospheres, we will use the Lyman-a and H2 emissions to constrain H and CH4 abundances in the upper atmosphere. We will then compare the results with state of the art models of photochemistry and global circulation in order to characterize the interplay of photochemistry, dynamics, and redistribution of energy that shapes the upper atmosphere through the changing seasons during the Cassini mission.

This project is directly responsive to the Cassini Data Analysis Program. It utilizes data obtained by the Cassini mission and includes data analysis tasks. The data are transformative and the proposal includes theory and modeling tasks that will produce significant science results on the chemistry and dynamics in Saturn's atmosphere. The proposal addresses multiple Cassini science objectives, including Determine the vertical structure of the atmosphere, in particular, how its composition, cloud properties, density, and temperature vary with height, Understand the horizontal motions of the atmosphere, Study how the atmosphere varies with time, and Investigate the relationship between the ionosphere, the magnetic field, and the plasma environment .

Xuanye Ma/Embry-Riddle Aeronautical University, Inc.
Plasma Radial Transport Processes in Saturn's Magnetosphere

Goal: Plasma radial transport in Saturn's magnetosphere is a fundamental process that is still poorly understood, despite decades of theoretical, observational, and modeling studies. The steady-state configuration of the inner magnetosphere requires a net radial outward plasma transport process without net magnetic flux transport. The frozen-in condition requires the magnetic flux in the inner magnetosphere to move outward with the plasma, thus, there must be an inward flow to refill the magnetic flux in the inner magnetosphere. It is widely believed that magnetodisc reconnection plays a critical role in the stretched magnetic field configuration (i.e., Vasyliunas cycle). In contrast, the centrifugal interchange instability associated with convective motion in the ionosphere has been suggested to be the major transport mechanism in the inner magnetosphere. In the inner and middle magnetosphere of Saturn, several Cassini instruments regularly observe signatures of injections, which are likely due to the inward motion of suprathermal plasma or energetic particle flux that is exchanged for colder, denser outward moving plasma. Meanwhile, both in situ data and Cassini energetic neutral atom (ENA) imaging have revealed a second class of injections, which seems to be more global in nature, less filamentary, and does not have the same qualitative features as a bundle of interchanging flux tubes. It appears that such injections are a consequence of magnetotail reconnection. It is not known how far inward this type of injected particles can reach and why they stop moving further inward. For a rapidly rotating planet both the flux tube entropy and flux tube content are expected to play important roles for the radial transport process. Thus, the scientific objective of this study is to comprehensively understand the radial plasma transport in Saturn's magnetosphere by addressing the following compelling Scientific Questions:

1. What are the radial profiles of flux tube entropy and flux tube content at different local times.
2. How far inward can different types of injections travel and what is the mechanism and physical processes associated with different types of injection.
3. How do different ion species and energetic particles move during the inward injections.

Methodology: These questions will be addressed by using both observational data analysis (i.e., Cassini) and numerical simulation. The steady state model of Saturn's magnetosphere obtained from the well-known 2-D steady state model provides the overall perspective of the magnetospheric stability properties. The three-dimensional Rayleigh-Taylor instability (i.e., akin to the centrifugal interchange instability) will be investigated by both MHD and hybrid simulations. The mesoscale MHD model solved in spherical coordinates will address the radial transport process in a more realistic configuration. Test particle simulations will be applied to examine the motion of energetic particles, and results will be verified with the hybrid simulation or observational data whenever possible. Cassini data will be used to provide inputs to the Caudal model for estimating the flux tube entropy, flux tube content for injection events, and also to estimate the penetration distance.

Relevance: This proposed study will use Cassini data to explore the compelling plasma radial transport and circulation problems with the help of theoretical analysis and computational tools, which will definitely enhance the utilization of data obtained by the Cassini mission. Thus, the proposed study is best fit for the CDAP program. The proposed study also directly related to Analyze the properties and processes in planetary magnetospheres in NASA's Planetary Decadal Survey.

Marzia Parisi/Jet Propulsion Laboratory
Probing the small-scale atmospheric features of Saturn by using Slepian functions to interpret Cassini Gravity Science data

Background, Goals and Objectives: The strong winds of Saturn dominate the high-degree gravity field of the planet by displacing large masses within the atmosphere. Hence, the determination of Saturn s high-degree field is key to probe the characteristics of the small-scale atmospheric circulation, energy transport and deep interior. During the Grand Finale, the Cassini spacecraft flew between the planet and its rings, with five orbits successfully devoted to the measurement of Saturn's gravitational field. The Doppler tracking data were acquired by NASA's and ESA's ground stations. The Cassini orbit was inclined and eccentric, approaching Saturn at low altitudes (2600-3900 km) for a limited time and over a narrow equatorial belt. The traditional approach using spherical harmonic functions requires uniform data coverage over the sphere to guarantee orthonormality (independence), especially for high degrees, whose detectability rapidly decreases with distance. As a result, while Saturn's low-degree (<10) field was determined with good accuracy [1], the signal of the fine structure of the atmosphere was buried below the uncertainty level. The objective of this proposal is to constrain the small-scale structure (<1000 km) of the deep zonal winds of Saturn, down to several thousand kilometers. The proposal will address science goals such as: (i) How do eddies interact to drive the deep atmospheric flows? (ii) How does momentum converge at low latitudes driving the equatorial superrotation? (iii) What sets the size and strength of the atmospheric midlatitude jets? (iv) Can small-scale structures in the gravity field identify interior convection columns, which have been hypothesized to exist in the interior of giant planets? This will be accomplished by using an innovative approach that employs Slepian functions [2] to analyze and interpret the Grand Finale data from the Radio Science Subsystem (RSS). These functions, which are optimized for a chosen subdomain (latitudinal belt), will match the Cassini observational geometry, and significantly improve the current knowledge of the high-degree and asymmetric gravity field of Saturn.

Methodology: The investigation of the small-scale dynamics of Saturn's atmosphere is based on the analysis of the Cassini Grand Finale RSS data to estimate the optimized Slepian coefficients. In-house software will be used for the retrieval of sky frequencies (i.e. the carrier frequencies as received at the ground station, including the Doppler effect due to the spacecraft motion), as well as orbit determination codes for the retrieval of parameters of interest through the analysis of Doppler residuals. The data analysis will constitute the base for the scientific interpretation. Optimization algorithms based on thermal wind balance will be employed to determine the depth of the small-scale atmospheric circulation [3]. Preliminary numerical simulations carried out by the team and based on the reconstructed Cassini trajectory show that it is possible to generate a set of Slepian functions which perform optimally in the limited range of latitudes observed by Cassini. They also predict that the wind-induced gravity signal expressed with Slepian coefficients is above the uncertainty level if the winds extend down at least a few thousand kilometers [3], and can therefore be used to probe the atmosphere and deep interiors, where differential rotation is suppressed.

Relevance: The proposed work will determine the high-degree gravity field of Saturn, which remains undetermined to date with the traditional spherical harmonic approach. The scientific objectives will maximize the scientific return of the Cassini gravity data and expand the existing knowledge of gas giants atmospheric dynamics and interiors. By addressing the proposed scientific goals, this project will have implications for a wide range of questions concerning the evolution and energy transport of Saturn's atmosphere and internal structure.

D Alex Patthoff/Planetary Science Institute
Ongoing activity at Enceladus: A search through time

Goals and Objectives. Saturn's small ice-covered moon Enceladus was first viewed in high resolution by the Voyager 1 and 2 spacecraft in 1980 and 1981, respectively. Roughly a quarter century later, the Cassini spacecraft began imaging the icy world at an even higher resolution. These missions revealed a surprisingly youthful surface and eventually provided evidence for present-day geyser-like activity on the satellite. For this proposal, we aim to determine if Enceladus experienced any detectable geological changes between the Voyager era and Cassini's arrival in the Saturn system, or at any time during the Cassini mission. We seek to constrain if any geological changes, such as the growth of a fracture or the movement of a ridge, are visible on the surface of Enceladus. We also seek to determine if the moon's icy shell experienced any motion due to nonsynchronous rotation (NSR), or true polar wander (TPW). The relatively long gap between Voyager images and Cassini, and the nearly 13 years Cassini spent in orbit around Saturn, may be enough to find differences between the data sets. If no changes or evidence for motion are found, we will still be able to set a lower limit on the modern period of NSR and an upper limit on the rate of geologic resurfacing. If changes are observed, it would be the first documentation of geological changes on an airless icy satellite and provide a crucial input for crater rate models, surface age determinations, and/or the tectonic and stress history of Enceladus. For this study we have 2 major objectives:

Objective 1: Determine if any surface geological changes occurred between the time of the Voyager images and the Cassini mission, or during the Cassini mission.

Objective 2: Determine if Enceladus experienced any nonsynchronous rotation or true polar wander between the time of the Voyager images and the Cassini mission.

Approach and Methodology. This work will use Cassini Imaging Science Subsystem (ISS) images and Voyager ISS images. First, we will select appropriate image pairs for comparison. We will compare Cassini images to the same regions imaged by Voyager, for Cassini-Voyager image pairs. Additionally, we will use Cassini images of the same areas but taken at different times and analyze them for differences. We will match Cassini-Voyager and Cassini-Cassini image pairs as closely as possible in resolution, filter, and viewing and lighting geometry. We will first coregister and reproject each image pair, and then make precise measurements of observable surface features to look for changes in the size, shape, or brightness of features due to geologic activity, or changes in absolute feature location in a way consistent with NSR or TPW.

Relevance. This work is relevant to CDAP because it would conduct scientific investigations utilizing primarily data obtained by the Cassini mission, specifically the ISS instrument, to constrain the geologic history of Saturn's moon Enceladus. Our work would seek to explore and observe the objects in the solar system to understand how they formed and evolve, specifically Enceladus, by examining the recent geological evolution of the satellite. This work would use both Cassini and Voyager images; however, no other program allows our proposed level of analysis of Cassini images and our work is therefore not relevant to other programs.

Paul Romani, NASA GSFC. Science-PI Shiblee Barua, USRA
Interpreting Cassini CIRS data with a Photochemical Model using Improved ab initio Reaction Rate Coefficients

OBJECTIVES: Spectra taken by the Cassini Composite Infrared Spectrometer (CIRS) can be used to retrieve vertical temperature profiles and mole fractions of trace gases in the 100 to 500 km region of Titan's atmosphere. The retrieved mole fractions, along with the mole fraction predictions from a photochemical model, can be used to infer dynamics in Titan's atmosphere if it can be shown that the transport life-time is shorter than the photochemical life-time. In addition, the chemical evolution of Titan's atmosphere, haze formation rate, etc. can be deduced by comparing the retrieved mole fractions with the photochemical model predictions. However, previous studies and global sensitivity analyses have shown that large errors exist in Titan photochemical model predictions. These model errors originate mainly from the uncertainties in the low-temperature (i.e., 70 200 K) rate coefficients of key radical neutral reactions. Experimental rate coefficients for such low-T reactions are difficult, if not impossible, to measure, and the lab data are often associated with large errors due to the uncertainties in determining the absolute concentrations of the radical species. Therefore, we propose application of high-level ab initio quantum chemical methods to calculate accurate rate coefficients, and then incorporate these rate coefficients to improve the mole fraction predictions of an existing Titan photochemical model. We will use calibrated CIRS data to retrieve vertical temperature profiles and carry out spectral analyses, which will enable us to assess the impact of our calculated ab initio rate coefficients on our photochemical model predictions. With this improved photochemical model, we will advance our understanding of Titan's fascinating atmospheric chemical factory.

METHODOLOGY: We will use high-level quantum chemical methods to calculate accurate rate coefficients for reactions that have not yet been studied in the lab under Titan conditions. We will perform our rate-coefficient calculations employing ab initio electron correlation methods such as CASPT2, MRCI, CCSD(T), etc. Next, we will retrieve vertical temperature profiles from calibrated CIRS data using the radiative transfer program NEMESIS (Non-linear Optimal Estimator for MultivariatE Spectral analySIS). Then we will use the ab initio rate coefficients and the retrieved vertical temperatures to improve the mole fraction predictions in an existing Titan photochemical model. Finally, we will use the improved mole fraction predictions to generate synthetic spectra, which will be compared against calibrated CIRS spectra to assess the overall impact of our calculated ab initio rate coefficients on the model predictions. Direct comparison between our generated synthetic spectra and CIRS spectra is an essential step as small mole fraction and/or temperature changes can have a dramatic change in the spectra.

RELEVANCE: Our proposed work is answering to the call in the Programmatic Overview (Section 1.1) of CDAP. Specific goals of the project include: 1) retrieval of vertical temperature profiles from calibrated CIRS data (responds to Cassini mission data analysis tasks), and 2) calculation of ab initio rate coefficients to improve Titan model mole fraction predictions, and generating new synthetic spectra for comparison against calibrated CIRS spectra (responds to non-data-analysis tasks that are necessary to analyze or interpret the data, or to enhance the use of mission data). Our calculated rate coefficients, vertical temperature profiles, volume mixing ratio (VMR) or mole fraction profiles, and generated synthetic spectra will be made available to the scientific community through NASA's PDS Atmospheres node.

Emilie Royer/Planetary Science Institute
Surface Composition of the Icy Satellites of Saturn from an ultraviolet perspective

The structure and composition of the surfaces of icy satellites are affected by primarily exogenic processes, such as E ring grain bombardment and plasma and electron interactions. We propose to investigate the effects of these processes on the surfaces of the inner large icy Saturnian satellites (Mimas, Tethys, Enceladus, Dione and Rhea) through photometric and compositional analyses in the UV region (110-190nm), using mainly data from the Cassini Ultraviolet Imaging Spectrograph (UVIS) instrument. This wavelength region is particularly sensitive to radiation products that are the results of weathering processes. The investigation will provide critical insight into the evolution of the moons regoliths and a better understanding of the interactions between the satellites, the E-ring and Saturn's magnetosphere. In addition, results will be placed in a broader context by including previously-published data from the Hubble Space Telescope (HST). The updated photometric models applied to these older datasets will be complementary to the interpretation of the UVIS data. The key objective is to explore various candidate species for composition and water ice contamination, to produce a broad composition map for each satellite, and assess their potential for endogenic activities.

We propose to start our investigation by analyzing the photometric properties of the five inner large icy Saturnian satellites using the UVIS data. This first modeling step will provide input parameters for the spectral modeling task. Previously published phase curves of Mimas, Tethys and Dione at 180 nm will be updated by adding the entirety of the Cassini data, from the beginning to the end of mission and the first 180 nm phase curves for Enceladus and Rhea will be added. The Hapke photometric model will be used to retrieve the albedo as well as the scattering and texture (roughness and porosity) properties of each satellites. The composition analysis of the icy surfaces will be our second and main step of the project. We will investigate candidate species such as ozone (O3), hydrogen peroxide (H2O2), ammonia (NH3), iron-rich nanograins, and Pluto tholins, which all have absorption features at the FUV wavelengths. However, a recent report of hydrazine monohydrate as principal contaminant of the water ice at Rhea will have us prioritizing this contaminant among the others, for all satellites. Our model will also include an investigation of the water ice grain size, as the UV spectra of the icy satellites exhibit a water ice absorption edge centered near 165 nm, the position of which is sensitive to grain size. The photometric and composition analysis will be first performed on disk-integrated spectra and then on disk-resolved spectra on specific locations of interest. At each step of the project, data from HST will be compared with the Cassini-UVIS observations, in order to perform comparative planetology across the Saturnian icy satellites and across UV and visible wavelengths.

Our investigation has the objective to enhance the scientific return of the Cassini mission by broadening the interpretation of Cassini data relative to icy satellite regolith structure and composition and is thus relevant to CDAP as stated in section 1.1 of appendix C.10 in the ROSES 2021 Research Announcement.

Lauren Schurmeier/University of Hawaii, Honolulu
The Influence of Clathrates on Titan's Ice Shell

Titan’s surface is an organic-rich world, unique in many ways. Its surface is blanketed with solid organics, produced by the irreversible photochemical breakdown of methane. The atmosphere rains liquid methane and ethane onto the surface. Impact craters are absent near the poles and they are anomalously shallow elsewhere. We hypothesize that many of these unusual geologic processes and the persistence of Titan’s atmospheric methane may be significantly influenced by the presence of methane or ethane clathrate that is expected to exist in the upper ice shell. Methane and ethane clathrate differ from water ice in three notable ways: significantly lower thermal conductivity, greater strength, and the ability to destabilize if thermally perturbed. We propose to investigate the influence of clathrates on the thermophysical properties of Titan’s ice shell and how they influence brittle and ductile behavior. These properties may affect the relaxation of craters, the movement of fluids in the ice shell, and the potentially explosive destabilization of the lithosphere.

The proposed research will include two tasks to address the following objectives. In Task 1, we will evaluate the thermal and physical (brittle vs. ductile) state of Titan’s ice shell with a focus on the insulating effects of clathrates and surficial organic deposits by calculating thermal profiles and lithospheric strength envelopes. In Task 2, we will assess the extent to which relaxation of impact crater topography is facilitated by the presence of clathrates using viscoelastic finite element modeling and use these results to constrain the clathrate thickness. The overall goal of this work is to determine how Titan’s clathrate- and organic-rich crust influences the thermophysical properties and the brittle vs. ductile behavior of the ice shell, and to evaluate if the thermally insulating effects can produce the unusual observed morphologies of impact craters.

The proposed work primarily requires the use of Cassini datasets: SAR imagery, SARTopo, and altimetry, and is therefore relevant to the CDAP objective of enhancing the scientific return of Cassini mission data. The project is responsive to the Cassini mission's goal of inferring Titan's internal structure and its ability to store and transport organic molecules.

Lawrence Sromovsky/University of Wisconsin, Madison
Saturn's local and seasonal aerosol variations inferred from Cassini combined UV, visual, and near-IR observations

BACKGROUND: Observations of Saturn by the Hubble Space Telescope since 1994 and by Cassini from 2004 through much of 2017 have spanned almost one Saturn year (29.5 earth years). Yet a consistent picture of the seasonal variations in Saturn's haze and cloud structure has been elusive. Prior work has been hampered by use of differing combinations of bandpass filters, lack of spectral range and resolution, and until recently, uncertainty in the mixing ratio of methane, which is a key barometer of the pressure boundaries of cloud layers. Cassini observations provide an opportunity to address these issues. From Cassini/VIMS observations in regions of low aerosol optical depth, and in storm regions with significant deep convection, the existence of ammonia ice cloud layers was finally established quantitatively, and the presence of horizontal structure in a deeper cloud layer was also revealed by 5-micron VIMS observations. VIMS observations from short wavelength visual through near infrared up to 5.2 microns, and the combined spectral effects of scattered sunlight and thermal emission, provide powerful constraints when applied simultaneously. But so far that has happened only once, in a recent regional study of the evolution of north polar clouds between 2012 and 2017.

OBJECTIVES: To better constrain the spatial and temporal/seasonal variations of chromophore and aerosol layers and gas composition on Saturn using a consistent model structure and consistent observational constraints, we propose to: (1) Extend the limited prior VIMS-based analysis of composition and aerosols in the polar regions to cover more time steps to characterize the difference in polar seasonal evolution; (2) Extend the analysis to characterize the latitude band structure of both entire hemispheres and their seasonal changes. (3) Analyze the 2010-2011 Great Storm's wake region to extend the characterization of its temporal evolution in cloud structure and composition for another 5 years as it returns to pre-storm conditions. (4) Greatly improve constraints on trace gas distributions by use of averaging techniques to enhance signal to noise ratios.

METHODOLOGY: We will use a model structure consisting of 4-5 aerosol layers with a parameterized chromophore model of real and imaginary refractive indices. Aerosol model and gas profile parameters will be constrained by simultaneous fitting of model spectra to the measured VIMS visual and near-IR spectra, assisted by UV ISS observations to better constrain properties of chromophores. Using the wide range of

VIMS wavelengths from 0.35 to 5.15 microns as well as scattering plus thermal emission and UV observations by ISS, we will achieve new levels of constraints on cloud particle composition, trace gas profiles, and chromophore characteristics.

RELEVANCE: The proposed analysis would use Cassini observations to enhance understanding of Saturn's cloud structure and composition. The proposed effort relies almost exclusively on Cassini observations of Saturn and satisfies the CDAP program objective to enhance the scientific return of the Cassini mission by broadening the scientific participation in the analysis and interpretation of data returned by the mission.

Xinting Yu/University of California, Santa Cruz
Comparing the material properties of Titan aerosols and laboratory-made aerosol analogs

Background: Organics produced from photolysis and radiolysis play important roles in various physical and chemical processes on Titan. In Titan's atmosphere, complex refractory organic haze particles directly interact with radiation and alter Titan's radiation budget. The haze particles can interact with condensable organic species, forming clouds and indirectly impacting the radiation budget. The atmospheric aerosols can settle on the surface as well, forming organic dunes. In order to understand these large-scale physical processes on Titan, a comprehensive understanding of the haze is necessary. Because there has been no aerosol sample returned from Titan, laboratory-synthesized analogs called tholins have been used as the model material for the organics on Titan. Since the concept of tholins was first introduced by [1], multiple laboratories with different setups have synthesized Titan tholins and have characterized them to different extents. However, there have been no systematic studies to compare the material properties of different tholins and determine the resemblance of these laboratory-synthesized Titan aerosol analogs to the aerosols formed in Titan's atmosphere and the organic sediments on Titan's surface.

Objectives: We propose to 1) conduct a comprehensive comparative study between tholin samples produced under different experimental conditions (pressure, temperature, energy source, gas mixture) in three different laboratories; 2) use the Huygens probe and Cassini spacecraft data and compare the properties of the actual aerosols and surface materials on Titan and laboratory-made aerosol analogs. The proposed research seeks to provide the Titan community with the answers to the following fundamental questions: 1) What are the differences and similarities in material properties between various laboratory-synthesized Titan aerosol analogs (tholins), and what experimental conditions cause the differences? 2) What is the possible range of material properties of tholins? 3) To what extent do tholins resemble actual aerosols and surface sediments on Titan, and how could their material properties affect our understanding of large-scale processes on Titan?

Methods: To achieve these objectives, we will conduct a comparative study of tholin samples produced from several nitrogen (N_2)/methane (CH_4) gas mixtures in three independent laboratory facilities (Lab A, B, C, see Expertise and Resources document).

These facilities have different experimental setups and experimental conditions, and we want to identify the critical experimental conditions/setups that control the material properties of tholins. We will characterize two important material properties: 1) surface properties, including surface energy through contact angle measurements; and 2) electrical properties, including the complex permittivity through a permittivity measurement bench. With the measured material properties of the tholin samples, we propose to establish the link between surface, electrical, and optical properties of tholins and aerosol/organic sediments on Titan using the Lifshitz theory and the Maxwell relationship. In addition, we propose to retrieve optical properties of the aerosols using the Huygens Descent Imager Spectral Radiometer (DISR) measurements, as well as the electrical properties of the surface sediments using the Huygens permittivity, waves, and altimetry (PWA) instrument and the Cassini-RADAR measurements. We will then be able to calculate the surface and optical properties of the surface organic sediments, the surface and electrical properties of the haze particles, and compare them with the properties of the laboratory-made analogs. Lastly, we will use the retrieved properties to make predictions for processes happening on Titan.

Discovery Data Analysis Program
Abstracts of Selected Proposals
(NNH21ZDA001N-DDAP)

Below are the abstracts of proposals selected for funding for the Discovery Data Analysis program. Principal Investigator (PI) name, institution, and proposal title are also included. 31 proposals were received in response to this opportunity. On March 31, 2022, 9 proposals were selected for funding.

Ariel Deutsch/Bay Area Environmental Research Institute, Inc.
The Mercury HOllows Retrieval NETwork (HORNET): Machine learning-driven mapping to assess hollow formation and evolution on the surface of Mercury

Unique to Mercury, hollows are small, shallow depressions that likely formed via volatile loss and appear to be very geologically young. Today, important questions remain about the origin and evolution of hollows. To help address these questions, our objectives in the proposed work are to: (1) determine the global distribution of hollows at various degradation states on Mercury, (2) determine how hollows are spatially correlated with local thermal environments, topography, and host units, (3) constrain hollow growth rates and determine if new hollows formed or existing hollows grew during the 4+ years of orbital operations by the MErcury Surface, Space ENvironment, GEochemistry and Ranging (MESSENGER) spacecraft, and (4) evaluate hypotheses related to hollow formation and evolution. To meet these objectives, we will train a convolutional neural network, the Mercury Hollows Retrieval NETwork (HORNET), to automatically detect hollows in visible-wavelength images, retrieve their positions, classify their degradation state, map their shapes, and measure their surface area, ellipticity, and long-axis orientation. We will implement HORNET on MESSENGER Narrow Angle Camera (NAC) images and produce a global catalogue of hollows and their characteristics for the proposed scientific analyses. Our global hollow catalogue will be archived on the Planetary Data Systems (PDS) Geosciences Node to encourage a broad community of researchers to work with our data and enable additional scientific analyses related to hollows.

Hollow detections will be analyzed in context of their global distribution and local thermal, topographic, and geologic settings to analyze various controls on the presence, size, shape, and degradation state of hollows. Hollow detections will also be analyzed with respect to image-acquisition time to constrain growth rates and to assess possible hollow formation and activity over MESSENGER's lifetime. Finally, we will synthesize the results and evaluate hypotheses related to the origin and evolution of hollows, with implications for the present-day distribution of subsurface volatiles and lag deposits on Mercury. The scientific analyses proposed in this work will produce 3 peer-reviewed publications related to the nature, origin, and evolution of hollows on Mercury and will be shared with the community at both Mercury-focused and also broader, planetary conferences.

This work is relevant to DDAP because it will enhance the science return from NASA's MESSENGER mission. Novel analysis techniques, including machine learning, will be applied to MESSENGER NAC data to investigate questions related to the distribution, growth, and development of sublimation features. This work is particularly exciting and timely for the Mercury science community because of the imminent arrival of BepiColombo at Mercury in 2025. The Mercury HORNET could eventually be infused with ESA/JAXA BepiColombo visible-wavelength images using transfer-learning principles to allow for immediate and optimized progress in the global mapping of hollows, enabling efficient studies of surface change detection and possible hollow growth sequences.

Overall, this work will provide a nuanced understanding of hollow development sequences, addressing important open science questions related to geologically-recent and potentially-ongoing volatile activity on Mercury, with relevance for volatile-driven landscape evolution on other airless terrestrial bodies, including the Moon and Ceres.

Robert Herrick/University Of Alaska, Fairbanks
Constraining the effects of impactor properties on crater morphology using MESSENGER data

While some function of impactor energy and/or momentum is universally acknowledged as being responsible for a crater's final volume on a given planetary surface, it has long been a source of debate whether the nature of the impactor (e.g., asteroidal versus cometary) can have a discernable effect on the final shape or morphology of a multi-kilometer impact crater. Resolving this question in the affirmative would provide a pathway to observationally constraining the relative proportions of asteroidal versus cometary impactors, while a negative answer means that differences between craters of similar size on a planet are likely due only to differences in near-surface geology. Mercury's proximity to the Sun means that it should have a mix of impactor types that have a range of impact velocities spanning several tens of kilometers per second, making it an optimal place to look for impactor effects on crater morphology. The best empirical evidence for impactor effects would be two craters that are different in shape or morphology but that are of identical size and located in identical geological settings. It is proposed here to test for impactor effects on final crater appearance by studying hundreds of pairs of Mercurian craters that are similar in diameter and located short distances from each other in the same geologic provinces. Data from the MErcury Surface, Space ENvironment, GEochem-istry, and Ranging mission (MESSENGER) will be used to make observations regarding the morphology, planform, topography, and surface geology of the craters. Differences in crater shape and appearance for the full sampling, and selected subsamples, of these proximal pairs will be quantitatively analyzed to search for patterns and trends indicative of impactor effects on crater shape and morphology. These compiled observations will be evaluated against existing hypotheses. The proposed work addresses questions in planetary science using publicly released data from the MESSENGER Discovery mission and is therefore relevant to the Discovery Data Analysis Program.

Kynan Hughson/University Of Alaska, Anchorage
Chill Hills: Exploring Ceres' Hydrology and Geology Through Pingo-like Morphologies

Like Earth and Mars, Ceres has abundant reserves of ground ice. On Earth, ice-cored hills in periglacial environments known as pingos are important indicators of extant and extinct groundwater systems and hydrogeologic properties. High resolution Dawn spacecraft observations over Occator and Urvara craters on Ceres revealed an abundance of small hills, many of which bear significant similarities to terrestrial pingos. Similar features have also been observed on Mars, but their nature and origin remain open questions. These pingo-shaped hills on Ceres have diameters as large as approximately 1000 meters and are resolvable to as little as several 10s of meters. A large fraction of these features occur in areas suspected of melting, or of being covered by water-rich melt during or shortly after impact, and now contain high concentrations of subsurface ice. This further suggests a possible genetic similarity to pingos. These pingo candidates represent unique science targets whose investigation may provide significant insights into the geological, hydrological, and astrobiological properties of Ceres. We propose a three phased science program that will: Phase I, Identify, qualitatively classify, and geologically contextualize small hills on Ceres; Phase II, Quantify the morphometry of identified cerean hills, as well as those of possible hill-form analogs on Earth; and Phase III, Use this knowledge to inform their interpretation through comparative planetology.

Phase I: We will use geologic mapping and spatial clustering techniques to identify and morphologically classify pingo candidates on Ceres. These hills will be analyzed for context and correlation with geologic units and structures identified in published maps of Occator, Urvara, and the intervening region in order to determine their regional- and local-scale geologic affinities. Non-parametric clustering algorithms will be applied to identify major centers of hill formation and will aid in determining if any of the hills are meaningfully correlated with surface geological structures or structure traces.

Phase II: We will use high-resolution Dawn stereo topography to characterize various morphometric aspects of the identified anomalous hills on Ceres. We will then collect similar morphometric data from potential terrestrial morphological analogs such as pingos, volcanic cones, karst hills, kames, and drumlins.

Phase III: We will then use these data to identify systematic morphological traits in common between the cerean hills and various potential terrestrial analogs using statistical comparative planetology. This analysis will inform the genetic interpretation of the cerean hills and quantitatively estimate their morphometric similarity to pingos and other terrestrial hill-forms.

These anomalous hills on Ceres represent a potential class of ice-rich landforms never before observed on a small body. Our multifaceted data analysis and interpretation approach will achieve our goal of providing complementary and independent evaluations of the geological and geospatial nature of small anomalous hills on Ceres and quantitatively establishing their morphometric similarity to various terrestrial hills of known genesis. By better constraining the structural and geological relationships, geospatial distribution, and morphometric affinities of these potential pingo candidates, this investigation will provide insights into the nature and evolution of possible hydrogeologic systems near the surface of Ceres.

Lauren Jozwiak/Johns Hopkins University
Exploring the Earliest Stages of Explosive Volcanism on Mercury

The surface of Mercury is dominated by two broad classes of geologic features, effusive volcanic plains, and compressional thrust faults. This geologic history mirrors the thermal evolution of a one plate planet, early heating and expansion supports effusive volcanism, while the switch to cooling and contraction shuts off volcanic production and promotes the formation of compressional thrust faults. While the data returned by the MESSENGER mission broadly supported this history, the mission also discovered an unexpected form of volcanism, explosive volcanism, in numerous locations across the planet. Explosive volcanism provided evidence for a significant volatile fraction in Mercury's interior, something previous formation models didn't consider as a possibility. Determining the timing and characteristics of these explosive volcanic vents in important for understanding the formation and thermal evolution of Mercury.
Stratigraphic studies of explosive vent location have revealed that some vents could be less than 1 Ga, and morphologic studies building on these results have suggested that nearly all recognized vents on Mercury are significantly younger than previously supposed. These results, in fact, lead to a geologic conundrum wherein the explosive volcanic period of Mercury's history is significantly divorced from the main phase of effusive volcanism. This leads to the natural question of what, if any, volcanic processes filled this intermediate period of Mercury's history, and what do these volcanic morphologies reveal about the fraction and distribution of volatiles in Mercury's interior? In order to investigate this missing" era of volcanism, we propose an analysis leveraging MDIS image data, MLA altimetry data, and MASCS spectral data. Our investigation will be comprised of three primary data analysis steps: 1) characterize, 2) explore, 3) synthesize. In tasks 1 and 2, we will characterize the geomorphological and spectrological signatures of the oldest known explosive vents and pyroclastic deposits on Mercury; additionally, we will utilize the MLA dataset to produce topographic distinguishers for vents vs. impact craters. We will then systematically explore the MDIS and MASCS datasets for these signatures a process which has not yet been undertaken given the initial stochastic methods of vent discovery. Finally, we will synthesize the geomorphological and spectroscopic findings to produce an index of vent candidates, ranked by confidence of identification, and probability of originating in the missing geologic era. The proposed investigations are relevant to DDAP and will fully utilize and plumb the depths of the MESSENGER MDIS and MASCS dataset, while also leveraging the MLA dataset.

Carl Schmidt/Boston University
Mercury's Escaping Sodium Tail

Objective: MESSENGER has shown that sodium is both the primary species in Mercury's exosphere and the dominant planetary ion in its magnetosphere. The proposed work seeks to better understand the energy characteristics of Mercury's sodium. Within this collisionless exosphere, Mercury's gas is not intrinsically thermal. Moreover, its energy distribution likely reflects a combination of individual energy distributions, each associated with one of the multiple sources sustaining the exosphere. Disentangling the relative contributions of these different sources has proven difficult, but is possible by characterizing and quantifying the exosphere's variability, its spatial distribution, and in particular its escaping population. We will address three Key Science Questions (KSQs) central to our field's understanding of the Hermean atmosphere:

(1) What is the photo-ionization lifetime of sodium atoms in our solar system?
(2) What is the characteristic energy distribution of Mercury's sodium gas?
(3) How do meteorites and plasma events affect Mercury's atmospheric escape?

Methodology: Our study will analyze MESSENGER UltraViolet and Visible Spectrometer (UVVS) data along-side concurrent ground-based datasets of the distant sodium tail. These simultaneous observations of the bound exosphere and escaping tail serve as an important metric: they partition the energy distribution at the escape threshold. Our objectives leverage the fact that this threshold is not simply fixed at the escape velocity. Rather, escape trajectories are achieved at lower speeds, and the threshold point has a known modulation due to strong radiation pressure that strips away the exosphere. This force from sunlight can exceed half the gravitational force. It varies steeply with the planet's season. A quantitative probe of true velocity distribution function (VDF) of the gas is thus provided by this seasonal shifting of the energy threshold for atoms to escape. The VDF determines how long atoms take to escape Mercury and therefore transit times to the distant tail. The tail's falloff with distance can thereby empirically constrain the Na lifetime, which remains uncertain and is based upon theoretical ionization cross-sections.

Significance: The proposed analysis would resolve fundamental problems in our understanding of the processes that sustain Mercury's thin atmosphere. Past UVVS analysis has largely portrayed Mercury's atmosphere as seasonal, while the proposed research would quantify episodic phenomena. In the process, we propose to measure the photolysis lifetime of sodium, a physical constant with broad applicability throughout our solar system.

Yinsi Shou/University Of Michigan, Ann Arbor
What can we learn from comparison of Rosetta in-situ and remote measurements of the coma of comet 67P

The Rosetta mission made unprecedented and successful measurements of the coma of comet 67P/Churyumov-Gerasimenko using multiple instruments, for over two years and all the way from 3.8 au through perihelion at 1.3 au and then out again to 3.7 au. These data offer a great opportunity to study the comet under different conditions, very active to less active over a wide range of heliocentric distances. The data gathered by the closely and continuously monitoring spacecraft can provide the distribution maps of many important volatile species, which can lead to a better understanding of the formation of comets. A spherical harmonics inversion method has been developed and applied to ROSINA DFMS mass spectrometer measurements to obtain potential surface activity maps of H_2O, CO_2, CO and O_2 on the nucleus of comet 67P averaged over large time slices of the mission. The same method has also been applied to VIRTIS-M spectral images and VIRTIS-H spectra to derive the activity maps of H_2O and CO_2. Here we propose to apply an improved method to many species in the ROSINA/DFMS measurements and H_2O, CO, CH_3OH and NH_3 observed by MIRO. The previous inversion method calculated the best coefficients of the spherical harmonics of activity maps, while the new method obtains the relative potential activity for many triangular surface facets, after dividing the nucleus surface into 1000 facets. In the previous method, the activity maps were assumed to be functions of latitude and longitude, i.e., two areas on the bi-lobed nucleus at different locations but with the same latitude and longitude were enforced to have the same activity. The new method eliminates any possible artificial results and provides higher surface resolution.

In addition, the measurements of the submillimeter radio telescope MIRO complemented that of ROSINA. Because MIRO measured H_2O, CO, CH_3OH and NH_3, which were also measured by ROSINA. In addition, one MIRO measurement is the integrated result of the number densities and a function of temperatures along the line-of-sight. The gas close to the nucleus also contributes to the measured signal and provides better constraints to the inversion method. The mass spectrometer measured the local gas at Rosetta relatively farther from the nucleus where detailed information of the distribution of the source region at the nucleus has been smeared out.

Our major scientific goals are (1) To determine the potential surface activity distributions of H_2O CO, CH_3OH, and NH_3 from submillimeter radio measurements and mass spectrometer measurements, (2) To determine the change in surface activity distribution of H_2O, CO, CH_3OH and NH_3 as a function of time over the mission, (3) To investigate the spatial correlations among the activity regions of a suite of major parent species measured by ROSINA/DFMS, i.e., H_2O, CO_2, CO, O_2, C_2H_5OH, C_2H_6, CH_3OH, CH_4, CS_2, H_2CO, H_2S, HCN, NH_3, and OCS, (4) To derive the global production rates based on the analytical model and fully kinetic Direct Simulation Monte Carlo Model (DSMC) model, (5) To investigate the discrepancies and agreements between the results obtained from in-situ and remote measurements.

All of the data from ROSINA and MIRO required for this investigation are already archived in the Small Bodies Node of the Planetary Data System or publicly available, thus making this study appropriate for the Discovery Data Analysis Program. The team includes investigators and collaborators with all the necessary expertise and experience including analysis tools for the data in question, calibration of the data and an intimate knowledge of all the necessary details. Analysis tools include the new inversion method and the DSMC comet coma model.

Michael Sori/Purdue University
Geophysical and geological tests of Ceres' crustal composition

Ceres, the most accessible ice-rich planetary body, is a location ripe for learning about the structure and processes of the icy moons and dwarf planets in the Solar System. Analysis of data from NASA's Dawn spacecraft have revealed that Ceres has a ~40-km-thick crust that is relatively strong and has density ~1300 kg/m3. These inferences have proven valuable, but a range of compositions might be able to fit these constraints. Most previous studies have argued that the crust must be composed of <40% ice (ice" always refers to H2O ice in this document), with the rest of the crust being some mixture of clathrate hydrates, salts, silicates, and/or organic material. However, recent laboratory experiments have shown that ice might plausibly be stronger than previously assumed, which could allow for >40% ice content in the crust. Thus, how much ice exists in Ceres' crust a quantity that is critical for understanding of a wide array of geomorphological and geophysical processes is largely unknown.

This proposal seeks to test the hypothesis that Ceres' crust is ice-rich using Dawn datasets and geophysical models. First, we will use finite element method (FEM) models of viscous relaxation of Cerean topography to determine if craters can be retained over geological history when recent rheological experiments are considered. These rheological experiments indicate that water ice could be stronger than previously thought under conditions relevant to Ceres. Second, we will measure and analyze the slopes of 100s of crater walls to determine the degree to which viscous relaxation, if any, has operated in modifying the landscape. Third, we will use geomorphological analysis to constrain ice content in the large, mid-latitude craters that are of special importance to quantifying viscous relaxation of the Cerean crust. The combined approach of comprehensive data analysis and numerical modeling will quantitatively determine the allowable quantity of ice on Ceres.

We seek to determine the possible crustal compositions of Ceres by analyzing image and topography datasets from the Dawn mission and interpreting them using geophysical FEM models. Analysis of Dawn data and the use of numerical modeling to interpret Dawn data is explicitly responsive to DDAP, as defined in the C.11 call for proposals.

Jordan Steckloff/Planetary Science Institute
Investigating the Geophysical Control of 67P/Churyumov-Gerasimenk's Outburst Plumes

Scientific Goals
Cometary outbursts (transient, rapid material ejections from the comet's nucleus) have been observed from the ground for decades, many of which appear to result from the ejection of highly collimated plumes of materials from the comet's nucleus. Recently, the Rosetta mission to comet 67P/Churyumov-Gerasimenko has provided the first high-

resolution observations of such outburst plumes as they leave the nucleus. Long thought to be controlled by internal processes, Rosetta revealed that some outburst plumes result from mass-wasting events at the surface of the nucleus. Further analysis revealed that the morphology of some of these outburst plumes are consistent with avalanches of material moving downslope into active regions on the nucleus. However, the effects of topography, geomorphology, and material properties on the appearance of mass-wasting-driven outburst plumes has not been studied. For example, differences in the morphology of the avalanching region and material, active area shape and composition, slope structures, and solar phase angle may result in different appearances and behaviors of outbursting regions. We propose to systematically investigate how differences in these surface structures and materials affect the behavior and morphology of outburst plumes, and constrain which outbursts on 67P could be driven by mass-wasting.

Methodology
We will use numerical models to explore how geophysical processes and geomorphological structures on the surface of Comet 67P affect the appearance and behavior of comet outbursts. These models use sublimative thermodynamics and rarefied gas dynamics to simulate the interactions between dust grains and between dust grains and sublimating gases outgassing near the surface of the nucleus. We will use these numerical models, already developed to simulate plumes on on active comets and other small bodies, to conduct a sensitivity study that investigates how different shapes and compositions of the avalanche source material and active area affect observed outburst plume morphology. We will also simulate different surface structures observed in the shape of 67P to understand how such structures affect the appearance and behavior of the observed outburst plumes. The outputs of these models will be compared to Rosetta observations, to connect the observed outbursts with geophysical processes at the surface of the nucleus.

Relevance to DDAP
The Discovery Data Analysis Program (DDAP) solicitation calls for proposals of that enhance the scientific return of Discovery Program missions and broaden the scientific participation in the analysis of data, both recent and archived, collected by Discovery missions." Although Rosetta was not a Discovery mission, Rosetta data analysis is supported by the Discovery program (&through DDAP)." This proposed work will use observations of outbursts and surface structures made by the Rosetta OSIRIS and NAVCAM instruments to understand how geophysical processes control outburst plumes, and is therefore within the scope of DDAP. Beyond direct data analysis tasks, DDAP allows for theory and modeling tasks that are not data analysis but are necessary to analyze or interpret the data [and] tasks that are not data analysis but that significantly enhance the use of facilitate the interpretation of Discovery mission data," provided that the results of such tasks are incorporate[d]...into the analysis or interpretation of Discovery mission data." Since the proposed modeling tasks are critical to interpreting Rosetta's observations of outburst plumes to understand the geophysical control of their appearance and morphology, our modeling tasks are within scope of the DDAP. Furthermore, the Solar System Workings solicitation calls for proposals that are not

appropriate for any Data Analysis Program Element," and therefore excludes our proposed investigation.

Weijie Sun/University Of Michigan, Ann Arbor
Solar wind influences on planetary ions in Mercury's high-latitude magnetosphere

Studies from MESSENGER's measurements have found that the planetary originated ions (mostly sodium-group ions, Na+-group ions) account for around 10% of the ions in Mercury's magnetosphere. However, how the planetary ions distribute in the high latitude magnetosphere and how they depend on Mercury's orbital phase (i.e., the true anomaly angle, TAA) have not been sufficiently investigated with in situ measurements. Furthermore, Mercury's magnetosphere is under continuous influence from the intense solar wind. Magnetopause reconnection can open planetary magnetic field lines with one end connecting to the solar wind and the other end to the planet's magnetic field. The solar wind particles can transport along with the open magnetic field lines injected into the magnetosphere, which would eventually sputter the planet's surface beneath the cusp. How the magnetopause reconnection influences the solar wind precipitation underneath the cusp and how the distribution and transport of the planetary ions depend on the magnetopause reconnection also have not been sufficiently investigated by the in situ measurements from MESSENGER.
This proposal will investigate the properties of Na+-group ions and the solar wind influences in Mercury's high-latitude magnetosphere. The high-latitude magnetosphere includes the northern cusp, the magnetosheath equatorward of the northern cusp, the magnetosheath and solar wind tailward of the southern cusp, and the southern plasma mantle, which were well sampled by MESSENGER. We propose to answer the following compelling questions:
Q1. How do the Na+-group ions distribute in Mercury's high latitude magnetosphere and how do the distributions depend on the true anomaly angle (TAA)?
Q2. Are the solar wind precipitation rates enhanced in Mercury's northern cusp during the intervals of intense magnetopause reconnection?
Q3. Are the Na+-group ions in the high-latitude magnetosphere enhanced during the intervals of magnetopause reconnection?
Q4. What is the escape rate of Na+-group ions through the high latitude magnetosphere? How does the escape rate depend on the TAA or magnetopause reconnection?
The investigation of Na+-group ions in Mercury's high-latitude magnetosphere will consider the effects of the TAA as well as the magnetopause reconnection. The magnetopause reconnection conditions will be revealed by the properties of flux transfer events (FTEs) observed near the magnetopause. In the case that planetary ions show clear dependency with the TAAs, we will consider the effects of the magnetopause reconnection at fixed TAAs. We propose to carry out a coordinated investigation rooted in MESSENGER data analysis and complemented by test particle tracing in a global Hall-MHD simulation to understand how planetary ions depend on the TAA and magnetopause reconnection and how they transport in Mercury's high-latitude magnetosphere.
MESSENGER provided 16 Mercury years of in situ measurements, which enable us to investigate both the long-term and short-term variations of the planetary ions. The

proposed tasks will employ the measurements from the Fast Imaging Plasma Spectrometer (FIPS) and the magnetometer (MAG). We will apply a well-established algorithm to identify FTEs on Mercury's magnetopause. The proposed research answers scientific questions concerning planetary ions and solar wind-magnetosphere-surface coupling at Mercury. The enhanced understanding of the distribution of planetary ions, solar wind injections into the cusp, and the escape of planetary ions will directly contribute to understanding the properties of planetary ions in Mercury's magnetosphere, which makes our proposed tasks highly appropriate for the ROSES 2021 DDAP program.

Planetary Instrument Concepts for the Advancement of Solar System Observations
Abstracts of Selected Proposals
(NNH21ZDA001N-PICASSO)

Below are the abstracts of proposals selected for funding for the Planetary Instrument Concepts for the Advancement of Solar System Observations program. Principal Investigator (PI) name, institution, and proposal title are also included. Twenty-two proposals were received in response to this opportunity. On October 26, 2022, six proposals were selected for funding.

Julie Brisset/University Of Central Florida
ORIGINS: Photothermal Spectroscopy for Planetary Sciences
21-PICASSO21-0010

We propose to develop a proof-of-concept instrument, the Organics and Regolith In-situ Grain Investigation using Near-range photothermal Spectroscopy (ORIGINS), that can non-destructively analyze planetary surfaces (in particular small bodies and icy moons), at a submicron level. To this purpose we will adapt and determine the applicability of a novel photothermal infrared (PT-IR) technology for the analysis of planetary surfaces. The instrument will be developed to perform chemical and structural analysis of the surfaces in-situ, without need for sample preparation and collection. While the principle of PT-IR has been demonstrated, the key components of a future flight-ready ORIGINS instrument need to be defined and prototyped in order to demonstrate the suitability of PT-IR for planetary science missions. The recent development of PT-IR in spectroscopy is an entirely new capability, which does not currently exist in the toolkit available to the planetary science community and has strong potential to increase the scientific value on future missions. The overall goal of the proposed project is to evaluate the applicability of the PT-IR technology to planetary surface sciences and determine its viability for future spaceflight missions.

Objectives - The project will (1) Design, build, and characterize a laboratory setup of the ORIGINS instrument. We will focus our efforts on creating a prototype with realistic sample-scanning times and energy usage. (2) Characterize the capability of the laboratory setup for analyzing various planetary surface analogues, including meteorite slabs, regolith simulants, and icy mixtures, to demonstrate its potential as a future spacecraft-based instrument.

Methods To address Objective 1, we will develop a system that can use efficient and small lasers such as quantum cascade lasers (QCLs), displays an optimized optical path to reduce the instrument footprint, and includes a customized 2D sample-scanning stage for planetary science missions. To address Objective 2, we will evaluate the spatial and spectral resolution of the ORIGINS system in detecting minerals and organics from planetary surface analogues, prepared as rough or granular surfaces.

Significance The PT-IR technology has significant advantages over current planetary in-situ analysis instruments:
-Better spatial resolution than conventional IR spectrometers. The PT-IR technique can be used to perform chemical analysis down to <500 nm, set by the diffraction limit of its visible beam, not the IR beam.
-Non-contact surface probing. This will preserve unique structural and chemical information on pristine material. In particular, the probing of icy surfaces and samples will be simplified.
-Compositional and structural analysis of the probed surface, at sub-micron resolutions, within a single instrument. This will allow chemical species localization and visualization of organic-mineral associations, combining the capabilities of several instruments into one.

Relevance The proposed development of ORIGINS will help overcome key limitations of conventional IR and is a first step towards an instrument that can be carried on landed missions to a variety of planetary bodies, in particular small bodies such as asteroids, comets, icy moons, as well as our Moon. This future ORIGINS instrument will provide for the following advances: (1) enhance our understanding of surface formation and evolution; (2) characterize the distribution of organics on planetary surfaces; (3) disentangle structural and compositional features in remote-sensing spectra of surfaces. It therefore is relevant for addressing several key questions of the Planetary Decadal Survey on the initial conditions and processes of Solar System formation, accretion of the Jovian planet satellites, and the primordial sources of organic matter. ORIGINS also aligns with the 2018 NASA Strategic Plan goals to expand human knowledge and understand the Solar System.

Kathryn Bywaters/Honeybee Robotics, Ltd.
OptiDrill: The next-generation instrumented drill
21-PICASSO21-0014

OptiDrill is a next-generation instrumented drill that enables the spatially-correlated mineralogy and microtexture identification within rocks and regolith. The 2022 ExoMars lander will have a drill embedded with the Mars Multispectral Imager for Subsurface Studies (Ma-MISS), which is a miniaturized infrared radiation (IR) spectrometer for borehole exploration; however, the main electronics will be on the lander and communication will occur through an interface based on slip ring devices (Coradini et al 2001). This accomplishment is a foundational advancement for in-situ planetary investigations but places significant constraints (increased: footprint, shielding and heating needs, and complicity) on the rover or lander. The next logical step is to develop an auger that contains the needed optical instruments.

Preserving unconsolidated regolith stratigraphy in samples and examining undisturbed grains is necessary for extraplanetary surface science to understand formation processes and characterize water content. Even using current-generation regolith-oriented coring drills, unconsolidated regolith stratigraphy can be destroyed in the process of extracting the core for study after drilling and water ice quickly sublimates once brought to the surface. The quantification of water ice in the regolith of the Moon and other planetary surfaces will continue to be an area of need for better understanding of what resources are accessible. In this technology development effort, OptiDrill, addresses the critical technology gap that exists for the study of undisturbed samples on other planetary surfaces.

Joel Campbell/NASA Langley Research Center
2-µm high-power, high repetition rate pulsed fiber laser for lidar Martian atmospheric CO2 and pressure profiling
21-PICASSO21-0024

Our diverse team of engineers and atmospheric physicists proposes to develop a 2-µm high-power, high-repetition rate fiber laser transmitter. This laser is the key component of the novel pulsed Differential Absorption Lidar (DIAL) for Martian atmospheric CO2 and pressure profiling. Martian atmosphere consists dominantly of CO2 (about 95%). Global CO2 observations, especially over polar regions where dry ice deposition frequently occurs, are urgently needed considering current pace of Mars's exploration. Furthermore, air pressure and pressure gradient are the most important variables for atmospheric dynamics that drive atmospheric motion and transports of mass, heat and momentum. Although air pressure is extremely important in characterizing Martian atmosphere, significant global observation gaps exist. There is no systematic observation of horizontal and vertical pressure distributions.

Martian atmospheric CO2 and pressure observations will fill this observational gap and address multiple planetary science priorities and objectives, especially those identified by the NASA Science Plan 2020   2024 and Planetary Science Decadal Survey. Improving our understating of Mars's atmosphere and its dynamics is crucial for future Mars exploration.

This project will take the advantage of the expertise from all team members, the success of the Earth's CO2 DIAL system development, and the invaluable progresses in fiber laser amplifier from multiple NASA SBIR projects. The laser of the transmitter will be developed from a single-mode distributed feedback (DFB) seed laser plus optical fiber amplifier system. Wavelength stabilization and variation monitoring will be applied to seed laser. For the high-power fiber-laser amplifier, technologies for both pulsed systems at nearby wavelengths and continuous-wave lasers at the needed ones will be used to achieve our requirements of 2-5 mJ laser pulse energy at a pulse repetition frequency of 1-2 kHz. A pulsed laser output of millijoules at 2.05 mm has not been accomplished before. With this laser, a transmitter toward future Martian CO2 DIAL system will be constructed.

Our research team consists of laser/lidar engineering, remote sensing, atmospheric science, and planetary science expertise. Our team has successfully collaborated for many years in many lidar technology development efforts, Earth's CO2 lidar development, atmospheric observational project collaborations, space/suborbital mission formulation, implementation, and execution processes. For this project, NASA Langley Research Center (LaRC) will be responsible for project management, overall system design and fabrication, instrument integration, and testing. AdValue Photonics, Inc will be in charge of the 2.05 µm amplifier manufacture and provide financially in-kind manpower support.

This is a 3-year project, starting on October 1, 2022. The entry TRL of the transmitter is 2 and at the end of this project the TRL will be at level 4. Furthermore, this proposed work will advance the entire Martian CO2 DIAL system to TRL-3.

Mool Gupta/University of Virginia, Charlottesville
A Miniaturized, Multifunctional, Microscopic Organic/Inorganic Composition Analytical Probe for Planetary in situ Spectroscopy
(MOCAPS)
21-PICASSO21-0011

MOCAPS (Miniaturized, Multifunctional, Microscopic Organic/Inorganic Composition Analytical Probe) for in-situ Spectroscopy is a compact, multi-modal micro-analysis probe for investigating the grain-scale composition of surface and sub-surface materials on rocky or icy bodies in the solar system. Innovative features include low mass (<1 kg), smaller size (15 x 12 x 8 cm), low power consumption (~1 W for the optical head), and incorporates multifunctional capability into a single focusable probe. Our innovative approach includes the incorporation of a focusing mechanism built into the probe, which reduces the requirements for precision placement and increases its resolution of samples at different focal planes with a minimum distance of a few millimeters between the probe and target. The proposed technology development supports combined Raman, fluorescence, Laser-Induced Breakdown Spectroscopy (LIBS), Laser Ablation Molecular Isotopic Spectrometry (LAMIS), and diffuse reflectance techniques using UV (266 nm) excitation at a spatial scale below 80 microns. MOCAPS will operate at 266 nm wavelength, which allows the use of a single laser and single spectrometer for micro-Raman and LIBS measurements, simplifying system design and reducing power draw relative to a multi-laser system. The Raman and fluorescence techniques enable the detection of organic and inorganic compounds, LIBS enables measurements of the elemental composition of target materials, and LAMIS enables isotopic measurements of a range of elements of biological and geological interest. The ability to accommodate these five complementary techniques with one probe is a powerful new development that has not yet been explored for in situ planetary mission instruments. This highly versatile probe will also be capable of supporting measurements of microscopic surface morphology through visible and infrared imaging, porosity through infrared imaging of laser-generated heat transport, and depth profiles of composition by ablation in the LIBS mode.

Some of the proposed major tasks for the project include: 1) Design, fabrication, and testing of the multi-modal optical head with autofocus capability, 2) Composition analysis algorithm development and testing, 3) Generation of test data for the asteroid, moon, and mars simulants, and 4) Optimization of weight, size, and power requirements. The proof of concept will be achieved by the integration on a breadboard that includes an in-house laser, spectrometer, and supporting optics fed by UV-rated optical fibers. The benefits of MOCAPS include efficient prospecting for planetary or asteroidal resources, the potential for assessing environmental damage to equipment exposed to harsh space environments, petrological and compositional analyses of planetary surface materials, including ices and organics, identification and quantification of biologically relevant compounds, and for assessing surface contamination to address planetary protection requirements. The instrument can be adapted for a robotic arm or used as a drop-in payload. A multidisciplinary team with expertise in lasers, optics and instrument development, planetary science, and NASA mission requirements has been formed to address the needs of the NASA PICASSO program. This proposal is directly relevant to the Planetary Science Division's strategic goals to develop new technologies that significantly improve measurement capabilities for planetary science missions." We will be leveraging support from the NASA SBIR Phase I and Phase II projects based on the 532 nm wavelength. The proposed effort is at Technology Readiness Level (TRL) of 2, satisfying the PICASSO requirement of low TRL instruments, with a goal of bringing it to TRL level 4, in preparation for future MATISSE program support.

Tilak Hewagama/NASA Goddard Space Flight Center
PReSSiC: Planetary Remote Sensing using SiC detectors
21-PICASSO21-0016

We propose to build, test, and validate High Sensitivity Silicon Carbide (SiC) Focal Plane Detectors for miniaturized instruments that can enable near-ultraviolet remote sensing of lunar surface and other planetary bodies. Silicon Carbide is a highly promising material, which has demonstrated at least two orders of magnitude better sensitivity in the Near Ultra-Violet (NUV) over previously used materials. To our knowledge, this project would be the first to harness 4H-SiC large format, small pixel, solar blind, linear detector arrays, with their unique material properties for the purposes, of integration into remote sensing planetary spectrometer instrumentation.

We would leverage the manufacturing and integration experience of our team in order to fabricate the detectors and then package and integrate them into a focal plane assembly. We will then test the focal plane array in a spectrometer set up we have in hand. Our team is uniquely equipped for this project given previous work that has been done with 4H-SiC material and would leverage previous developments that used SBIR, GOES-R and NASA/GSFC internal research and development funding. The work proposed by the project would raise the technology readiness level of these detectors from 2 to 4, with a future MATISSE proposal aimed at additional maturation of the detectors as a viable path for planetary instrumentation impacting science identified in the decadal survey.

The proposed 4H-SiC focal plane detectors would be able to obtain remote sensing radiance observations with a higher detectivity than previous generations of 200-340 nm

NUV spectrometers with a resolving power of R~200. The compact power, size and cost footprint of these detectors would enable important NUV observations of several different planetary targets, including the Moon, Icy Worlds, Io, small bodies such as comets and asteroids, and atmospheres of certain planets. The miniaturization of such detectors with readout electronics is also key to enabling NUV instrumentation in SmallSats or added to larger, conventional spacecraft as CubeSat ride share missions.

Adrian Tang/Jet Propulsion Laboratory
CMOS Digital Ground Penetrating Radar with Hardware Embedded Artificial Intelligence for Sub-Surface Exploration
21-PICASSO21-0017

A capability of imaging the subsurface of planetary bodies in the solar system is key to understanding their history, composition, and evolution. Probing these sub-surface environments is vital to answering a number of priority questions such as What were the initial stages, conditions and processes of solar system formation and the nature of interstellar mater that was incorporated?" in NASA Decadal Survey as well as closing Strategic Knowledge Gaps on the Moon, Mars, Phobos, and Deimos for future human explorations.

Current Ground penetrating radar (GPR) architectures are based on microwave devices which limit the flexibility and adaptability of these instruments to accommodate unexpected sub-surface conditions. This rigidness can become particularly challenging for planetary missions where a GPR radar is being considered in places where the surface and sub-surface conditions are not well understood or modelled. With a traditional microwave GPR, the system parameters (resolution, penetration depth) must be committed to by design prior to flight, which may later prove to be sub-optimal. For example RIMFAX on NASA's Mars 2020 rover contain many fixed-frequency or fixed-tuning" components (RF filters, mixers, amplifiers, &) that greatly limit the potential to adjust radar parameters (frequency, signal waveform, bandwidth,&) in-situ, as that would require changing these fixed RF components (for example changing filters to different bands). To address this challenge in planetary GPR instruments, our team proposes to develop an all-digital, in-situ reconfigurable Ultra-WideBand (UWB) ground-penetrating radar based on CMOS system-on-chip technology. This CMOS all-digital radar would allow for essentially all radar parameters (except the antenna) to be programmable in-situ (as there is no fixed-frequency or fixed bandwidth hardware), allowing a GPR instrument to adapt to an encountered near/sub-surface environment.

A second major challenge of GPR technology is the self-interference of the strong transmitted signal leaking into the receiver as the radar operates at long wavelengths with both transmitter and receiver placed in proximity. This self-interference limits the amount of power that can be transmitted without saturating the receiver, limiting the penetration capabilities of the instrument. To overcome this self-interference we propose to introduce a second signal pathway coupled directly to the receiver which is driven by a generative artificially intelligent network embedded inside the radar chip hardware. This AI network is tuned to generate and optimization a 180 deg phase copy of the Tx-to-Rx leakage which cancels out the power leakage into the receiver. This allows the radar to transmit more power without self-saturating via transmit to receive coupling, enabling far better penetration than a conventional GPR architecture.

The proposed 36 month PICASSO effort will mature the all-digital artificial intelligent GPR instrument concept from its current TRL of 2 (basic functions demonstrated) to a complete breadboard-style instrument providing an exit TRL of 4. Science operation will be validated through both laboratory and modest outdoor fielded testing.

Planetary Science and Technology Through Analog Research
Abstracts of selected proposals
(NNH21ZDA001N-PSTAR)

Below are the abstracts of proposals selected for funding for the PSTAR program. Principal Investigator (PI) name, institution, and proposal title are also included. 49 proposals were received in response to this opportunity. On April 7, 2022, 6 proposals were selected for funding.

Christopher German/Woods Hole Oceanographic Institution
Science and Technology for Ocean Worlds: Ice-Covered Chemosynthetic Ecosystems

Overview. This project will partner an established team (WHOI & JPL) with international polar scientists to investigate a serpentinizing seafloor hydrothermal system in the ice-covered Arctic Ocean at seafloor pressures that are intermediate between those projected for submarine vents on Enceladus and the deeper seafloor of Europa. The project responds to both the Science and Technology objectives of PSTAR.

Science. The Aurora vent field (82°N, Gakkel Ridge) lies beneath the most persistent multi-year ice in the Arctic Ocean. It shows clear geochemical evidence of ultramafic-influenced venting despite prior geological observations that the site is hosted in young volcanic basaltic rocks. This represents a novel geologic setting for submarine venting anywhere on Earth, but with particular potential to host abiotic organic synthesis. We hypothesize that the ultra-slow spreading Gakkel Ridge generates volcanism in such low volumes that only a thin veneer of basalt is extruded as a crust overlying uplifted mantle rocks. Thus, fracturing of the lithosphere allows seawater to circulate through both this young basaltic ocean crust and uppermost component of the underlying mantle. To test this, our colleagues at AWI have been funded to conduct a 2 cruise study of natural seismicity using their new icebreaker FS Polarstern, complemented by seafloor hydrothermal investigations during Cruise 2. PI German has been invited to sail as Co-Chief Scientist for the 2nd cruise and to lead our international team to survey and sample the seafloor vents at the Aurora field using WHOI's purpose built, 5000m-rated Nereid Under Ice vehicle. Our interdisciplinary project will integrate geological, geochemical and micro-biological investigations of the high temperature venting already photographed at Aurora. We will focus our efforts on associated low-temperature venting because that is where our most recent NASA funded work has revealed that the greatest potential for both (a) abiotic organic synthesis in ultramafic-influenced submarine vents and (b) the availability of chemical energy that can be exploited by microbial metabolisms (at temperatures <120°C).

Technology. Our use of Nereid Under Ice to dive to e4000m deep vents in the ice-covered Arctic Ocean will immediately meet two PSTAR goals: testing and application of a mobile science platform that will be used to conduct in situ sensing, and sample acquisition and handling at pressures in excess of those inferred for seafloor venting at Enceladus and approaching those anticipated for Europa. Our work will also focus on two further PSTAR goals: techniques for autonomous operations and intelligent systems and human/robotic interfaces. Building on our prior PSTAR research (autonomous water-column localization of hydrothermal fields), we will develop methods for autonomous localization, identification, and selection of low-temperature flow sites within a larger vent field (these low-T sites are now recognized as a high priority for astrobiology). We will conduct this work in shadow mode during Y1 Arctic field operations, and target full testing in partnership with NOAA OECI cruises in subsequent years. Once a (seafloor) target of interest has been identified, the next operational issue is how to land a mobile platform (location, orientation) to enable sample collection, manipulation and/or sensing. This challenge maps from present day deep ocean to future ocean world operations. Repositioning at the seafloor is costly (time, energy) and can compromise sampling sites. Accordingly, we will combine terrain relative navigation with 3D projection to transform sparse seafloor data into enhanced situational awareness for vehicle operators that will improve efficiency at Earth's seafloor and retire risks for landed operations on other Ocean Worlds.

Samuel Howell/Jet Propulsion Laboratory
ORCAA: Ocean Worlds Reconnaissance and Characterization of Astrobiological Analogs

The icy shell of Europa, an Ocean World orbiting Jupiter, may be geologically and hydrologically active, allowing ice and water to connect the chemistry of an oxidant-rich irradiated surface to that of a reducing active seafloor. Hydrologic connectivity may redistribute chemical energy and heat to establish reduction-oxidation (redox) potentials and create habitable niches.

We propose a Europa-analog subsurface liquid reservoir exploration mission in partnership with the Juneau Icefield Research Project (JIRP). This proposal will advance our understanding of interconnected habitable reservoirs within icy environments, enabled by planetary subsurface exploration technologies, and elucidate science operations for subsurface access missions. While the pressures and temperatures of the targeted reservoir in the Juneau Ice Field are similar to a reservoir a few kilometers beneath Europa's surface (~273 K, ~2.5 MPa), no terrestrial glacier is a perfect physical, chemical, or biological analog to Europa. However, we can elucidate the importance of the hydrological connectivity that may permit nutrient migration and the establishment of habitable or inhabited niches in planetary ice shells.

Objectives:

A. Science Fidelity: Sample a transect of melted glacial ice, and a liquid subglacial reservoir, to understand how energy and material fluxes, including the flow of oxidants, organics, and biomolecules migrating through the englacial realm, structure and intertwine subsurface icy ecosystems at and between key interfaces, to make predictions

for the generation, evolution, preservation, structure of icy habitable environments on Europa.
B. Technology Fidelity: Demonstrate subglacial reservoir access by a cryobot, emphasizing sample handling and cleanliness, autonomy, hazard mitigation, continuous sampling, real-time communication, continuous thermal management, and reliability.
C. Science Operations Fidelity: Simulate a condensed planetary reservoir access mission to determine how and when scientists and autonomous systems discover indicators of change in the physical environment, habitability, and biological communities, and to characterize the temporal and spatial fidelity requirements of observations.

Key Information:

Alaska's Juneau Icefield in hosts a transient subglacial lake beneath ~250 m of temperate ice, situated ~3 km from a supraglacial lake. Between the lakes is the Juneau Icefield Research Project (JIRP) Camp 10, with hard-walled accommodations and equipment. The site is accessible from Juneau by helicopter, and hosts the longest operating polar research and education program in North America, maximizing potential participation and training of future astrobiologists.

Surface-based planetary instrumentation includes a novel digital holographic microscope to quantify cellular activity, augmented by a fluorometer and compact Raman spectrometer to characterize populations and provide context. Molecular biomarkers redistributed from the surface will be tracked using a multimeter. The planetary surface payload will enable down-selection of key samples to be stabilized for later laboratory study, including chemical and bioinformatic analyses of microbial biomarkers to identify distinct populations.

The proposed work and technology demonstration meet the PSTAR objectives of furthering planetary and terrestrial science, innovating and demonstrating key planetary technologies, and advancing our understanding of science operations in these extreme, remote environments. These objectives directly address both the NASA SMD strategic plan and the stated position of the NASA Astrobiology Programs Network for Ocean Worlds (NOW).

Laura Kerber/Jet Propulsion Laboratory
Exploring Lunar Lava Layer Cliffs

This three-year, <150K/yr project will focus on the science and science operations strategies needed to achieve the lunar science goal of exploring the stratigraphy of a lunar mare pit. To accomplish this goal, we will use a “scarecrow” version of an extreme terrain rover and a suite of representative instruments to characterize a mare pit analog site at Tabernacle Hill lava field in Fillmore County, Utah. The resulting dataset will be used to create a “design simulation” in order to test science operations concepts and train the team to operate in a challenging pit environment. The same dataset will be used to understand the diversity and variability of the lava layers at the monogenetic, low-flux Tabernacle Hill lava field, a result that will be published in the terrestrial volcanological literature and used to inform data taking strategies for the Moon.

Background: Recent renewed interest in the Moon has led to the proliferation of scientific missions and technology demonstrations destined for the lunar surface, including as part of the Artemis and Commercial Lunar Payload Services (CLPS) Programs. The diversity of both lunar mission goals and destinations will challenge NASA's traditional approach to rover operations, which have been dominated by a Mars paradigm for the last 25 years. The new class of robotic exploration missions will face some challenges in common, including near real-time operations, with communications delays in the low 10s of seconds, and short mission timelines (many constrained to the two-week span of the lunar day).

A mission to a lunar pit would challenge concept of operations architectures in new ways. In addition to near real-time operations and a two-week mission length, a lunar pit mission would have to accommodate several major challenges stemming from the unusual geometry of the mare pit namely the extreme-terrain, near-vertical operations environment represented by the mare pit wall. In addition, any successful lunar pit mission would have to develop a data-collection strategy that is parsimonious but also representative, despite the fact that the diversity of the target stratigraphy is not known a priori. Steep slopes and cliffs are often sites of geological interest, as they represent a slice through the local stratigraphy, revealing relationships between geologic units. The relative instability of cliff faces means that they frequently expose unweathered sections of new rock ideal for many geological analyses. Developing science operations strategies for these kinds of geometries can feed-forward into near-term mission opportunities for the Moon as well as longer-term opportunities for Martian crater walls, Enceladus vents, and beyond.

This PSTAR proposal focuses on two major areas needed to enable the execution of a lunar pit mission: Science operations (focused on science decision-making, planning, and data collection and return), and Science (focused on assessing the spatial diversity of a lunar-analog lava field).

Methods: The proposed project leverages existing instruments and hardware and consists of three main activities. First, we will conduct a field campaign to Tabernacle Hill, Utah, a volcanic field with numerous pit craters, tubes, and exposed lava stratigraphies. We will collect a dense grid of data using cameras, a multispectral microimager, and a portable field XRF. From these raw data we will create data products (such as 2-D image mosaics, 3-D maps, MMI spectral cubes, and XRF measurements) in a transect down the lava layer wall. Second, the data collected from this field test will be integrated into the mission design simulation. A team of operators will use the collected data to choose a path down the wall, decide on contact science locations, and assess the data for sufficiency. Finally, the results will be report in the peer-reviewed literature.

Zachary Morse/Howard University, Inc.
Augmented Reality Data Visualization Analog Research Campaign (ARDVARC)

As part of the Artemis Program, NASA plans to begin building a sustained human presence on the Moon by sending astronauts to the lunar south pole to starting in 2024 (NASA, 2020). These crewed missions to the lunar surface will be preceded by and coincide with a number of robotic exploration missions to the same region (Dunbar, 2021). Unlike the Apollo lunar missions to the lunar equatorial region, the Artemis missions will encounter low-angle polar lighting conditions including long dark shadows and shaded topographic depressions that will make Extravehicular Activity (EVA) more difficult and dangerous. The Augmented Reality Data Visualization Analog Research Campaign (ARDVARC) is a proposed pair of lunar analog deployments that would assess: 1) the Concept of Operations (CONOPS) for a lunar rover deployed as a precursor mission to a low-angle lighting environment, and 2) the use of Augmented Reality (AR) and Virtual Reality (VR) data visualization based on precursor rover data to aid astronauts with navigation and scientific investigations in a low-angle lighting environment.

We plan to use basalt deposits in the San Francisco Volcanic Field (SFVF) near Flagstaff, Arizona, for the proposed field deployments. The geology in this location is analogous to the lunar surface and has been used since the Apollo era as a training site for lunar missions (Young et al., 2010; Gruener et al., 2013; Ross et al., 2013; Bleacher et al., 2015; and Vaughan et al., 2019). Analog operations will be conducted at night with bright near-horizon light sources to simulate conditions similar to those that the Artemis astronauts will experience at the lunar south pole. This analog scenario would underscore the challenges of conducting both rover and astronaut missions in a polar lighting environment, as well as highlight the usefulness of AR data visualization in low-angle lighting conditions. This proposal would adapt existing prototype AR visualization software for use in the analog mission scenarios. The proposing team includes multiple veterans of high fidelity analog rover and astronaut deployments as well as several members who are experts in conducting geologic field work in remote and extreme environments.

The proposed work is relevant to NASA's current exploration goals as lessons learned can directly impact ongoing planning for the Artemis program. The proposed work is also relevant to the NASA PSTAR program in the Science Operations and Technology areas as the fieldwork and the AR development would enable evaluation of both CONOPS in polar lighting environments and new technology relevant for future planetary surface exploration.

Feifei Qian/University Of Southern California
LASSIE: Legged Autonomous Surface Science In Analogue Environments

The overall study objective is to enhance scientific outcomes of robot-aided planetary explorations, by integrating high-mobility legged robots with embedded terrain-sensing technologies and cognitive human decision models. State-of-the-art rovers and robots typically operate based on pre-programmed agenda, and have limited capabilities to: i) effectively detect unexpected changes in terrain properties and responses and adjust locomotion or sampling strategies; and ii) autonomously identify scientifically-valuable observations and adjust exploration strategies. Such inefficiency can lead to critical mobility or sampling failures, and missed scientific discoveries. To bridge this gap, we propose to integrate legged mobility, direct-drive embedded terrain-sensing, and human-robot collaborative decision-making workflow, to enable terrain-sensible, discovery-driven legged robots that can effectively move, adaptively situate, and scientifically examine a wide range of planetary environments. We will conduct this research in two key planetary analogue sites that present well-defined gradients in regolith composition: White Sands Dune Field, New Mexico, and Mt. Hood, Oregon. Field sites will be complemented with laboratory experiments, to isolate controlling variables and test robot capabilities.

Our technology objective is to enable terrain-sensible adaptive sampling and mobility by deploying direct-drive multi-legged robots that can “feel” and interpret surface force responses via leg-terrain interactions. With this proprioceptive terrain-sensing capability, future planetary exploration robots can collect rich environment data at every step as they traverse planetary surfaces. This novel “sampling during locomotion” capability is distinct from wheeled rovers whose terrain sensing is too indirect to extract reliable and accurate geotechnical soil properties. The terrain-sensing legged robot strategy offers enhanced sampling accuracy, resolution, and locomotion efficiency.

Our Science Operations objective is to create a cognitively-enhanced human-robot collaborative sampling workflow that allows robots to participate in the scientific decision-making process and provide human scientists with targeted decision support to reduce cognitive overload and biases. Testing the human-robot collaborative science operation workflow in analogue sites will reveal how scientists refine hypotheses and adjust sampling strategies based on dynamic incoming observations. This enhanced decision-making transparency, integrated with the sampling during locomotion" technology, will lead to the creation of cognitively-compatible legged robotic assistants that can infer humans' dynamic scientific beliefs and aid with the identification of potentially valuable sampling targets to enhance scientific outcomes.

Our Science objective is to determine how the friction and erodibility of regolith admixtures is altered by surface crusts, coarse-grained lags and ice content. We will deploy the direct-drive legged robots to map spatial distributions of regolith strength across known environmental gradients at two analogue sites. We will simultaneously measure environmental parameters that control regolith strength, including: grain size and shape, soil moisture, chemical composition, and ice content. Laboratory experiments will examine the dependence of terrain force responses to robotic leg mechanical interactions on a variety of regolith simulants, with systematically varied grain properties and admixture content. Integration of laboratory and field data will inform how soil physical properties are connected to geology and climate, and may help to anticipate regolith properties on planetary surfaces.

The integrated science, technology, and operation objectives of our proposal will lower the risks and enhance the scientific rewards of planetary exploration.

Mahmooda Sultana/NASA Goddard Space Flight Center
Network for Assessment of Methane Activity in Space and Terrestrial Environments (NAMASTE)

Distributed chemical measurements are important to resolve spatiotemporal variation of key species on planetary surfaces, such as methane (CH4) on Mars and water on the Moon. We propose a field campaign to demonstrate the operation of a novel, versatile, miniaturized (250g, 12x8.9x2cm3, <3W), highly sensitive (down to part-per-billion concentration) and integrated in situ chemical sensing instrument under development for habitability assessment and the identification of life-related chemistry on planetary surfaces. As part of the field campaign, we will measure methane release from permafrost in Fairbanks, Alaska, in two different configurations: 1. single instrument in the second year and 2. a network of instruments in the third year. While our focus on this project will be on demonstrating fidelity to science operations and technology, this work will also provide important characterization of methane release from thawing permafrost. The main objectives are: 1. Demonstrate performance of this innovative instrument in the field; 2. develop, test and validate concept of mission operations for the chemical sensing instrument in two configurations. Validation of our instrumentation and operations concept in a terrestrial environment that provides an analog for spatially and temporally variable methane releases on Mars is required to assess mission architectures to measure methane on Mars in order to resolve its origins.

The chemical sensing instrument unambiguously identifies target trace gases on planets, moons and asteroids. The instrument includes a suite of nanomaterial-based chemical sensors, temperature and pressure sensors, readout, on-chip heaters and wireless communication, packaged in a self-contained unit. Most of the components are printed on a small substrate with innovative 3D micro and nanoscale printing techniques developed by our team. The ability to print different components of the instrument directly on the same chip eliminates the need to integrate individually fabricated components, making the packaging robust and significantly reducing the resource footprint of the overall instrument. The low resource footprint will not only enable trace gas measurements on low cost, small-scale missions such as SIMPLEX-class that would otherwise not be able include such measurement capabilities, but also allow us to send a network of these instruments to Mars to make distributed measurements and construct a spatial map of surface composition for species such as methane.

While permafrosts are not the perfect analog for methane sources on Mars, they still provide a great opportunity to demonstrate the operation of a highly promising instrument, as well as an instrument network, in a cold environment. In addition, our study will address the question of why remotely sensed methane measurements differ significantly from in situ methane measurements on Mars. We will compare our surface measurements to both vertically resolved flux tower measurements and measurements made by NASA Arctic   Boreal Vulnerability Experiment (ABoVE) on instrumented science flights to compare remotely sensed and in situ methane data. Finally, our work will address key science questions on the role of permafrost in a changing climate. Much of the permafrost in interior Alaska is just below freezing, making this large store of carbon potentially vulnerable to thaw resulting in emission of globally significant quantities of CH4.

To ensure the success of this integrated interdisciplinary field experiment, we have formed a highly competent team of instrument scientists, planetary scientists and Earth Scientists across NASA Goddard and University of Alaska. The proposed study responds directly to the PSTAR solicitation, as it would lower the risks associated with the operation of a novel instrument and measurement architecture in addition to developing operational capabilities through systems-level field testing in a relevant analog environment.

Planetary Protection Research Program
Abstracts of Selected Proposals
(NNH21ZDA001N-PPR)

Below are the abstracts of proposals selected for funding for the Planetary Protection Research program. Principal Investigator (PI) name, institution, and proposal title are also included. Ten proposals were received in response to this opportunity. On October 15, 2021, five proposals were selected for funding.

Murthy Gudipati/Jet Propulsion Laboratory
Survivability of Spacecraft-Associated Microbes under Simulated Radiation Environments of Europa and Other Icy Moons

For ongoing and future missions to Europa and other icy moons, it is important to distinguish potential indigenous life vs. forward contamination caused by spacecraft bioburden, which is of serious concern to safeguard science objectives of the missions. Similarly, spacecrafts can spend significant amounts of time in the radiation environments of these targets, providing opportunities to reduce bioburden. Thus, quantitative determination of the survivability of potential spacecraft-associated terrestrial microbial contaminants (SATMC) both in ice-like and on spacecraft-material-like environments is critical to constrain the models that estimate these processes.

Jovian magnetospheric radiation (protons, ions, and electrons with energies in the MeV range) could kill the SATMC, both on/in the spacecraft as well as on the Europa surface or near subsurface. MeV electrons can penetrate several centimeters through solids, and could significantly contribute to microbial reduction during orbit and/or after landing or crashing on the surface. The same processes could occur in Saturnian system with weaker (but still significant) MeV radiation flux.

However, there is a lack of direct laboratory experimental data on microbial survivability in high vacuum conditions and/or under realistic radiation environments. Electrons penetrate by far the deepest among the various charged radiation particles, making them the most likely source to reduce bioburden in the interior of a spacecraft. Bremsstrahlung (X-rays and gamma-rays) make their way through the materials farther and kill microbes at depth.

Existing work on microbial survivability under gamma radiation is only applicable for the secondary radiation (Bremsstrahlung). Attenuation and the energy deposition per unit depth (stopping power) is higher for electrons compared to the gamma radiation. As a result, non-linear effects control the damage of the microbial cells, necessitating laboratory work using realistic electron radiation.

Our goal is to determine, through laboratory studies, dose-vs-survivability of a variety of radiation-hard microbes representing SATMC and our team has the complementary expertise to achieve this multidisciplinary task. We will leverage our ongoing relationship with NIST (National Institute of Standards and Technology) and will use their MeV electron source. We will study the effect of vacuum (~1E-9 mbar) and low-temperatures (~100 K) representing the desiccating environmental conditions of space and Europa, with and without MeV electron irradiation. We will also determine microbial survivability under simulated liquid water pocket radiation environments.

We will test spacecraft materials coated, ice cores imbedded, as well as water-ice samples spiked with PP relevant microbes, in controlled conditions. Spacecraft materials will simulate the bioburden reduction of an orbiting craft receiving MeV electron doses during a mission. Ice cores with imbedded microbes will simulate the survivability of forward contamination for a lander or crashed spacecraft and the protective effect of surface ice in shielding these microbes from surface radiation. The liquid water samples simulate RTG-spacecraft crashing into and melting the ice, creating a potentially habitable niche for forward contamination.

Our study will provide the much-needed empirical data under realistic conditions which will help NASA researchers to develop models to calculate bioburden reduction through high-radiation environments, and the probability of contamination upon landing. This data is critical to provide more realistic inputs to biological survivability models used to assess the probability of contamination and to refine guidelines for forward bioburden contamination in the context of icy worlds such as Europa or Enceladus.

Andrew Schuerger/University Of Florida, Gainsville
Effects of Frost-Cycling on Microbial Survival and Growth under Simulated Martian Conditions

Habitable Zones (HZ) on Mars may be found at sites in which liquid water is periodically stable (e.g., melting frosts, inclusions within subsurface ices, recurring slope lineae). Such sites have been reported in low- and mid-latitudes on Mars. Some of these HZ sites might be labeled as Special Regions on Mars (see Rummel et al., 2014, Astrobiology, 14(11), 887-968), and thus, may require additional sanitation and sterilization protocols for spacecraft prior to launch.

We have developed methods for creating and melting frosts under simulated Martian conditions of 7 mbar, 80 to 20°C, and CO_2-enriched hypoxic atmospheres (called low-PTA conditions) within a Planetary Atmospheric Chamber. We have verified that the window for stable liquid water on Mars lies between 0 and 4°C at 7 mbar, and that the thickness of the frosts on rock surfaces can be controlled. Frost layers will be deposited on the upper surfaces of Mars analog soils at approx. 80°C. Warming of the frosts by simulated solar heating of analog soils begins to form liquid water at 0°C, and flowing liquid water can be observed at 7 mbar until the frosts dissipate between 5 and 7°C.

New experiments are proposed that will examine the critical nature of melting frosts on the survival and growth of microorganisms that are present on spacecraft materials or that might be dispersed onto rock or soil surfaces. All experiments will be conducted under simulated low-PTA Martian conditions using aluminum 6061 as a support material (i.e., coupons). Ten Mars analog soils (i.e., based on published rover and lander data) will be used to test the plausibility of dispersed spacecraft microbiota surviving and/or growing in the Martian regolith when liquid water is periodically supplied by melting frosts.

For survival experiments, the spore-forming bacteria Bacillus pumilus SAFR-032 (UV-resistant strain) and Bacillus subtilis 168 (not UV-resistant); and the non-spore forming bacteria Deinococcus radiodurans R1 (UV-resistant) and Enterococcus faecalis ATCC 29212 (desiccation resistant) will be tested for survival under simulated low-PTA conditions, solar UV-irradiation, and frost-cycling. The experiments will be extended from the typical 1-7 d time-steps seen in the current literature for Mars simulations to 28 days. UV irradiation and solar heating will be cycled daily in a coordinated process to match the melting of the frost layers by solar illumination.

For growth experiments four hypopiezotolerant bacteria (def., capable of growth at 7-12 mbar) will be tested for growth under simulated low-PTA conditions with and without frost-cycling that will periodically add liquid water to the Mars analog soils. The hypopiezotolerant bacteria Bacillus sp., Carnobacterium gilichinskyi, Exiguobacterium sibiricum, and Serratia liquefaciens (see Schuerger and Nicholson, 2016, Astrobiology, 16(2), 964-976) will be used for the growth experiments.

Results will indicate whether short-lived but daily additions of liquid water from melting frosts in Martian low- and mid-latitudes will alter the lethality of the UV environment and provide adequate sources of liquid water to permit the survival and growth of bacteria under Martian conditions. Based on the published literature of microbial survival and growth under simulated low-PTA conditions, and the process of frost-cycling on Mars, we predict that liquid water from melting frosts (1) will increase the lethality of the Martian environment by hydrating spores or cells, breaking dormancy, and weakening their survival capabilities; and (2) will not provide adequate liquid water to support microbial growth of proven hypopiezotolerant bacteria.

Emily Seto/Honeybee Robotics, Ltd.
Development of In-Flight and In-Situ Microbial Sterilization System using UV LEDs and Heaters to Prevent Re-contamination and Cross-contamination

The new era of sample return and life detection missions require development of sterilization strategies that will be crucial for meeting stringent requirements for both forward and backward planetary protection. This proposal directly responds to the NNH21ZDA001N-PPR call by examining new sterilization strategies for microbial reduction, utilizing the synergistic effects of multiple Ultraviolet radiation (UV) wavelengths in combination with and without heat. Ultraviolet radiation (UV:100-

400nm) is a no-touch passive sterilization approach for sensitive hardware and a well-known sterilant often used to inactivate microorganisms. UV kills mainly by direct effects; that is, the photon is absorbed by an important cellular component (like DNA), which is then altered and loses its functionality. The predominant usage of UV mercury lamps emits only one wavelength (254 nm) can be improved upon by using UV-LEDs which can be configured to emit certain wavelengths. This study will be the first known study to test various spore-forming organisms isolated in the cleanroom with a combination of selective UV LED wavelengths, with or without heat and vacuum. Heat is an approved microbial reduction technique for forward planetary protection and has been selected as a candidate for in-flight sterilization.

The goal of this study is to test and introduce optimized in-flight microbial reduction technology that will be used to mitigate 1) launch recontamination 2) cross contamination of sample-intimate surfaces during planetary sample collection and 3) contamination of sample return canisters for example, break-the-chain. In-flight sterilization capabilities have already been requested for future Mars Sample Return break-the-chain, making this technology development relevant for multiple NASA objectives. More specifically, for Mars Sample Return, the UV LEDs can be mounted on various locations in the CCRS (Capture Containment Return System) to remove contaminants from the exterior of the OS (Orbiting Sample) container. Additionally, this in-flight sterilization technology can be mounted near sample-intimate surfaces (such as drills) and irradiating and heating the surfaces to reduce cross-contamination between sample collection events on planetary bodies. For example, UV LEDs for drills will be in arranged in a circular configuration to not only irradiate drill of different shapes but also, to maximize the UV exposure from different angles. The current state-of-the art for mitigating launch recontamination includes biobarriers that have proven to be costly, not to mention the bulky nature of the structure may interfere with the limited space allocated for assembly. It is worth noting that the Phoenix Mars Lander mission used a deployable flight bio-barrier to protect its dry heat microbial reduction (DHMR)-treated robotic arm. However, flight bio-barriers typically represent a single-point failure element for mission critical components which adds risk.

The incorporation of strategically placed UV LEDs within the spacecraft can be a low power, cost effective, and flexible solution for reducing contamination. In general, our test data will be used to support the first in-flight sterilization technology for robotic exploration and a cutting-edge technological demonstration of UV LEDs in combination with or without heat for microbial reduction. The end result of optimizing and eventually implementing such emerging technologies benefits all NASA programs and disciplines whose underlying objectives involve planetary protection.

David Welch/Columbia University
Investigating Far-UVC Radiation to Reduce Microbial Burden During Spacecraft Assembly

The 2021 ROSES solicitation for Planetary Protection Research has a broad goal of limiting the biological contamination of other solar system bodies by terrestrial microorganisms. In this research we address the solicited research area of identifying and developing new methods and technologies to support microbial bioburden reduction techniques. The technology which we propose is the use of ultraviolet radiation with wavelengths in the range from 200-230 nm, known as the far-UVC, as a means of killing both microbial vegetative cells and spores. While traditional UV uses 254 nm radiation, which is a health hazard even at low doses so human exposure must be limited, far-UVC radiation can potentially be safely utilized as an antimicrobial while humans are present. A number of our published biological safety studies with far-UVC wavelengths show essentially no damage to skin or eyes, whereas exposures to widely used germicidal UV (254 nm) show significant damage. The efficacy of ultraviolet radiation as an antimicrobial agent is well documented, and our preliminary studies on efficacy against a variety of target organisms demonstrated that the far-UVC wavelengths have similar antimicrobial properties as 254 nm radiation. The differential effectiveness, with far-UVC radiation not harmful for human exposure yet capable of killing microorganisms, makes this an attractive solution for decreasing the microbial bioburden on spacecraft and spacecraft-associated hardware during spacecraft assembly. This technology could be particularly useful during time critical activities such as during Assembly, Test, and Launch Operations (ATLO), where microbial bioburden reduction could take place continuously and without any increase in the engineering scope of work. In addition, this technology could be useful in maintaining localized microbial cleanliness requirements within facilities occupied by multiple flight projects.

The focus of the proposed research will be an examination of the efficacy of far-UVC radiation for purposes specific to Planetary Protection implementation. One area of research will be to examine the efficacy against a range of spore forming and non-spore forming bacteria, including species previously isolated from spacecraft and associated surfaces during the spacecraft assembly process. These organisms have demonstrated tolerances to common forms of decontamination including gamma radiation, hydrogen peroxide, desiccation, and traditional UV (254 nm) thus exploring the efficacy of far-UVC radiation against them will provide relevant and worthwhile results. A second component we will explore is the performance of far-UVC radiation to reduce microbial burden on a variety of surfaces present during spacecraft assembly including metals, paints, and plastics. The efficacy of microbial reduction techniques can vary depending on the surface, so calculating a dose response for each surface is needed for a thorough evaluation of this antimicrobial approach. Finally, testing for possibilities of acquired tolerance to far-UVC exposure will be evaluated using a series of repeated exposures with an analysis of changes to microbial susceptibility.

This project is the first-ever assessment of far-UVC as a tool for reducing microbial bioburden for planetary protection applications. The efficacy data gathered from these goals, combined with both completed and ongoing safety studies, will provide a basis for NASA to evaluate this technology for implementation as a NASA approved microbial reduction technique .

Craig Zuhlke/University Of Nebraska, Lincoln

Rapid Sterilization of Spacecraft Hardware Using High Photon Fluxes from Femtosecond Pulsed Lasers

Post-sterilization handling of spacecraft hardware for testing and re-work requires frequent surface cleaning, re-sterilization, and planetary protection testing, leading to substantial resources and delays during the assembly process. Dry heat sterilization techniques are time-consuming, requiring several days of heat exposure. Furthermore, some essential components of spacecraft, such as optics and electronics, are not compatible with current sterilization techniques. We propose for the first time to use femtosecond lasers to deliver high photon fluxes from 35 fs laser pulses (~1 x 10^31 photons/(sec*cm^2), ~0.1 J/cm^2) onto finished surfaces for the sterilization of spacecraft components. Microorganisms have not experienced these high photon fluxes during evolutionary history and do not have protection mechanisms against them. A new laser-based rapid sterilization technique will substantially reduce the hardware processing, assembly time, and cost to help improve planetary protection implementation efforts; moreover, laser-based sterilization can be used on uneven surfaces and can reduce or remove cellular debris from non-viable microorganisms. The proposed research responds directly to this research area in the solicitation: Identify and provide proof-of-concept on new or improved methods, designs, technologies, techniques, and procedures to support planetary protection requirements for outbound and return sample missions.

The goal of this pilot study is to optimize laser parameters to sterilize spores on spacecraft metal components. Laser sterilization is likely to be compatible with a wide range of spacecraft materials, but compatibility can only be determined after we first determine the parameters necessary for effective sterilization. The outcome of the pilot study will provide critical parameters to determine spacecraft component compatibility. The long-term goal for this study is to establish ultrashort pulse laser-based techniques for high-speed sterilization of complex spacecraft components.

To meet the goal, we will pursue the following objectives:

Objective 1: Determine the optimum femtosecond laser parameters, including intensity, pulse count, pulse length, wavelength, and double-pulse spacing for killing viable bacterial spores.

Objective 2: Determine the compatibility of the femtosecond laser treatment to killing and removing bacterial spores on spacecraft components.

The proposed work will test several bacterial strains previously isolated from spacecraft surfaces, focusing on bacterial spores since they are the hardiest microorganisms present. Two forms of high photon flux will be investigated: (1) wavelength tuned femtosecond laser pulses in the infrared that are tuned to the resonance absorption of water within the spore/cell or femtosecond ultraviolet pulses, and (2) using femtosecond double-pulses (two pulses spaced picoseconds apart) to take advantage of time-dependent light-matter interactions processes in destroying spores/cells. NASA Ames will provide metal surfaces spiked with bacterial spores to University of Nebraska-Lincoln (UNL), where they will be illuminated with a range of femtosecond pulse parameters. Ames will analyze the spore structure damage and the survivability rates resulting from the illumination, using electron microscopy and a standard NASA spore assay. Modeling of first and second reflection laser intensities will be used to address compatibility with challenging complex surface shapes for killing spores hiding in any nooks, crannies, or other recesses on metal surfaces. Compatible spacecraft components will be identified based on optimized sterilization parameters and reported material damage thresholds. As a first-ever proof-of-concept for sterilization using femtosecond lasers, this work has the potential to provide a substantial advance not only for planetary protection but for a wide variety of ground-based applications.

Laboratory Analysis Returned Samples
Abstracts of Selected Proposals
(NNH21ZDA001N-LARS21)

Below are the abstracts of proposals selected for funding for the Laboratory Analysis Returned Samples program. Principal Investigator (PI) name, institution, and proposal title are also included. 8 proposals were received in response to this opportunity. On June 27, 2022, 3 proposals were selected for funding.

Elena Dobrica/University of Hawaii, Honolulu
Phosphates - trackers of metasomatic history of the Itokawa asteroid

Science Goals and Objectives: The role of aqueous fluids in the evolution of ordinary chondrite parent asteroids is one of the outstanding problems in cosmochemistry. In type 3.0-3.4 ordinary chondrites, the presence of fayalite, magnetite, phyllosilicates, and Fe,Ni-carbides has been attributed to H2O-CO2-bearing fluid-rock interaction. The Delta-17O of the fayalite and magnetite grains in these meteorites, ~50, suggests the presence of isotopically heavy water or water ices that accreted into the ordinary chondrite parent asteroids. Subsequent thermal metamorphism resulted in dehydration of phyllosilicates, significant loss of volatiles, chemical equilibration, and largely destroyed the evidence of fluid-rock interaction. However, some minerals in metamorphosed ordinary chondrites, such as phosphates, plagioclase, and chromite, grew and evolved during these processes. In addition, some ordinary chondrite regolith breccias, e.g., Monahans and Zag, experienced the addition of volatiles from the volatile-rich impactors.

In type 3.0 ordinary chondrites, phosphorous occurs mainly in Fe,Ni-metal and chondrule mesostasis. In equilibrated ordinary chondrites (EOCs), this phosphorous is oxidized, most likely by aqueous fluids, and is preferentially concentrated in various phosphates (e.g., apatite and merrillite). Some compositional differences of phosphates in H, L, and LL chondrites suggest variations in fluid chemistry on their parent bodies. Therefore, phosphates are potentially important chemical and isotopic (e.g., hydrogen, oxygen, fluorine, chlorine) trackers of metasomatic fluids in ordinary chondrite parent asteroids. Multiple grains of merrillite and apatite have been previously identified in samples of the S-type asteroid 25143 Itokawa returned by the JAXA Hayabusa spacecraft. Although textural occurrences of these phosphates have been documented, their chemical and isotopic compositions are poorly known. Here, we propose to measure chemical and oxygen isotopic compositions of the Itokawa phosphates and phosphates from several equilibrated L and LL ordinary chondrites. The data to be obtained will be used to (i) measure the abundance of volatiles and oxygen isotopic composition of the Itokawa and EOC phosphates to assess their similarities and differences, and (ii) examine the source of metasomatic fluids and their role during thermal metamorphism on the Itokawa asteroid.

Methodology: To achieve these goals, we propose to measure chemical and oxygen isotopic compositions of the Itokawa phosphates and phosphates from several equilibrated brecciated and non-brecciated L and LL ordinary chondrites. We will use SEM, EMPA, TEM, and SIMS at the University of Hawai'i (UH). We will focus on detecting and measuring the concentrations of volatile components (Cl, F, and OH) in these phosphates by VEELS and EDS using an aberration-corrected scanning TEM equipped with a monochromator and high-resolution electron energy-loss spectrometer. More specifically, to detect water in phosphates, we will use the VEELS. The ability to detect water in situ at the nanoscale has been already demonstrated in interplanetary dust particles. In addition, we propose to measure the O-isotope composition of phosphates in situ using the UH Cameca ims-1280.

Relevance: The LARS program goal is to maximize the science derived from planetary sample-return mission". In particular, our proposed work directly investigates: analytical studies of astromaterials already returned by planetary missions" as stated in Section 2 of C.16 Laboratory Analysis of Returned Samples of 2020 NASA-ROSES. The proposed work will analyze returned samples from the S-type Apollo asteroid, 25143 Itokawa, by the Hayabusa mission, run by the Japan Aerospace Exploration Agency (JAXA). Our proposed work falls under Analyze Returned Samples" which is supported under the LARS program.

Amy Jurewicz/Arizona State University
Advancing Genesis Mission Goals through Solar Wind Analysis and Technical Enabling

The work proposed will further Genesis Measurement and Science Objectives in two fundamental ways. First, we will measure solar wind samples, thereby meeting Genesis goals directly. Second, we will enable work by other PIs in the community in several ways, including direct technical support and advice, working in a consortium with other PIs (under the oversight of Genesis Curation) to remove surface contamination from collection surfaces to allow larger-area analyses, and encouraging collaboration of Genesis PIs with researchers from other scientific communities (e.g., solar physics and space weathering) to enhance the usefulness of the Genesis solar wind data.

Our proposed solar wind measurements extend previous work and are divided into five sub-Tasks. The focus is sub-Task (C1): measuring the Mg isotopic composition of the solar wind (SW) in all three regimes: interstream(slow), coronal hole(fast) and coronal mass ejection. We will revisit Mg isotopes in the bulk solar wind to refine our published ´25Mg, which had relatively large errors due to spatially variable amounts of 24MgH in analyses of Genesis diamond-like carbon (DLC). To complete this task, we will use the same procedures developed during our technical development study but, as regime samples contain less solar wind, will use the superior performance of Cameca IMS 1280 at U. HI, Manoa and intercalibrate our existing ICPMS-calibrated standard for instrumental fractionation to a lower dose implant. We will also implant half of that new standard with H to account for hydride formation.

Other sub-Tasks are: (C2) measuring SW Fe fluences in all three SW regimes; (C3) measuring SW Na precisely in bulk SW and all three SW regimes; (C4) calibrating the

Ca/Al ratio of bulk SW and all three SW regimes; and (C5) finishing work on the Fe/Mg composition of bulk SW. Sub-Task (C2) will use DLC and the same technique used for Mg isotopes on the ASU Cameca IMF 6f. Fractionation of SW from Photospheric composition is a function of first ionization potential (FIP). Fe and Mg have essentially the same FIP, but different masses. Differences in precise Fe/Mg ratios from each regime, if found, suggests that elemental mass fractionation needs to be a second-order correction for Genesis and a confirmation of a novel interpretation of spacecraft data offered by Pilleri et al. in 2015. (C3) will compare SW Na fluences from DLC vs. from silicon. We suspect that SW Na values from Genesis silicon are high due to radiation-induced migration of surface contamination. Na and Mg are low FIP elements of similar mass so the Genesis Na/Mg ratio from each regime should be solar, so (unexpected) variations in the ratio will spur solar physics modeling of SW formation. (C4) SW CaCa and Al have already been measured: we plan to calibrate the Al implant used as a standard, as the nominal doses of low-dose implants have been seen to deviate 40% from the certified value. If mass fractionations from (C2) are significant, Ca/Mg ratios from each regime will be compared to indicate if SW Ca also needs a small mass correction. SW Ca/Al and Ca/Mg values from (C4) will be used to more reliably model the amount of calcium aluminum inclusions incorporated into chondrite groups. (C5) finishes work on a Genesis baseline value for Fe/Mg using data from multiple laboratories, collector materials, and techniques.

Our proposed technical enabling of other Genesis PIs continues decades of effort. In addition to advising on the specifics of Genesis materials and collection conditions, we have provided flight-like materials and implants (reference and calibrated) for technique development, worked with Genesis Curation and other interested PIs to clean samples without disturbing solar wind. In addition, we collaborate with JSC to run the annual Genesis Solar Wind Sample Analysis and Techniques Workshop, where we bring in speakers that include solar physicists, engineers, and others to talk with Genesis PIs.

Alexander Meshik/Washington University
Analytical developments in preparation for multi-collector noble gas isotopic analyses of samples returned from asteroids Ryugu and Bennu

We propose to upgrade and refine our unique 8-multiplier noble gas mass spectrometer and to develop low background gas extraction and purification techniques to analyze isotopes of all noble gases in samples to be delivered by the Hayabusa-2 and OSIRIS-REx missions. The noble gases in these primitive asteroidal samples will provide invaluable information on the early stages of the Solar System formation. However, we expect to analyze samples much smaller than typically examined in our laboratory, especially if mineral separates are to be investigated.

The proposed work builds on our analytical developments and experience gained during extensive analyses of solar wind noble gases in Genesis collectors. We successfully and with high precision measured all noble gas isotopes therein. The analytical capabilities of our laboratory were recognized by JAXA, and we were selected for the Hayabusa-2 Initial Analysis Team.

Analytical precision is limited by statistical errors. Our Noblesse mass spectrometer was custom built in collaboration with Nu Instruments to reduce these errors, at that time specifically for the micro-analyses of solar wind noble gases captured by Genesis collectors. Its eight electron multipliers allow for significant improvements in the counting statistics. All currently available noble gas instruments have at maximum five multipliers, and nearly all mass spectrometers built in the past were single-collector instruments.

While the precision of noble gas analyses is generally determined by counting statistics, the accuracy depends on systematic errors caused by background (blank), isobaric interferences and memory effects. These error sources become especially significant for low count rate analyses. To reduce the blank and minimize exposure of the returned samples to the terrestrial environment, we will construct a miniature low-blank oven. Compared to laser extraction techniques already available in our laboratory, step-wise pyrolysis will provide more uniform heating and better temperature control, and thus allow for improved separation of trapped asteroidal gases from surficial components, including unlikely, but possible, traces of Xe propellant from the Hayabusa ion thrusters. A combination of extensive gettering and a palladium filter will be applied to reduce the hydrogen level in the ion source, which will minimize unresolvable interferences from protonated noble gas isotopes. Memory effects from previous analyses are a potential source of significant errors. Our mass spectrometer has been used exclusively for analyses of minute amounts of solar wind and small spikes of atmospheric noble gases for calibration. It has never been exposed to gases from meteorites, lunar soils, or samples containing fissiogenic/nucleogenic components.

Our multi-collector instrument was optimized for micro-analyses of heavy noble gases. We propose to extend its applicability to He and Ne measurements by using the pseudo high-resolution approach. We plan substantial modifications of the Noblesse software that will enable us to control the pulse height distribution of the electron multipliers at low count rates and correct for drift of the magnetic field during peak-jumping.

A major part of the efforts and expenses will be related to substantial modification of the ion detection system. The current multipliers will be replaced by more reliable ones that are less susceptible to damage from vacuum bake-out. The conversion dynode will be modified for improved peak shape and reduced cross-talk". We will be supported by the Nu Instruments team, with whom we have a longstanding working relationship since the development of our multi-collector instrument.

The proposed work is in line with the first category of the LARS program: development of laboratory instrumentation and/or advanced techniques required for the analysis of returned samples".

Planetary Science Early Career Award
Abstracts of selected proposals
(NNH21ZDA001N-ECA)

Below are the abstracts of proposals selected for funding for the ECA program. Principal Investigator (PI) name, institution, and proposal title are also included. 27 proposals were received in response to this opportunity, 5 of which were selected for funding.

Timothy Goudge/University Of Texas, Austin
Uncrewed Aerial Vehicles for Planetary Surface Exploration Research, Outreach, and Teaching

The use of uncrewed aerial vehicles (UAVs) for studying geologic processes has rapidly increased over the past decade, thanks to the availability of UAV systems and the ease with which collected data can constrain landscape properties (e.g., topography). UAVs have also made their way into the realm of planetary exploration, with NASA's Ingenuity helicopter technology demonstration showing that a small UAV can be effectively used to aid in situ exploration and produce scientific data. Furthermore, the upcoming Dragonfly mission will land, and fly, a (large) UAV on Titan to constrain its surface composition and geology, as well as its atmospheric properties. In addition to providing a platform for planetary exploration, visualization of UAV data can be incredibly effective for education, outreach, and improving the accessibility of planetary geoscience research. This proposal for an Early Career Award (ECA) would directly support the professional development of PI Dr. Timothy Goudge, allowing me to pursue novel research, teaching, and outreach opportunities centered on the use of UAVs for exploring planetary landscapes. The proposed effort will help me build a research program focused on using the unique lens of remote sensing to understand the record of surface processes captured in the topography of planetary bodies. The support from an ECA would help me progress towards my career goal of seamlessly integrating teaching, outreach and research in my program. Finally, the work enabled by this ECA would further my career goal of becoming involved in planning and operations of planetary exploration missions, as the proposed research is of direct relevance to both ongoing and planned NASA Planetary Science Division (PSD) missions. The first proposed task will involve collection of high-resolution images of sedimentary outcrop in Utah to be used in building digital outcrop models (DOMs) at a range of resolutions (from flights at different altitudes). DOM-based observations of outcrop stratigraphy will be compared with field-based observations to answer the question: At what resolution(s) is stratigraphic information critical for interpreting paleoenvironmental properties lost from DOMs? This question is key for optimizing UAV flights over sedimentary outcrop, for example on Mars, weighing flight time vs. coverage vs. science return. Depending on the lifetime of the Ingenuity helicopter, results may be directly relevant to this ongoing PSD mission. Regardless, the results will inform future mission concepts, as Ingenuity has shown the potential for planetary exploration via UAV. This task will be directly integrated with scientific outreach, with production of 3D printed models of the studied outcrops displayed, along with 3D printed models of Mars topography for comparison, at two university-wide open house events: Explore UT and Girl Day at UT Austin. The second proposed task will involve collection of images and lidar data of an active sedimentary system on North Padre Island, Texas. The field site has both active dune fields and coastal environments, process-analogs to potential sites of exploration for the Dragonfly mission. Stereo-image-derived topography will be compared with lidar-derived topography to answer the question: Is the higher precision topography from lidar necessary for studying active sedimentary systems, or are stereo-images sufficient? The answer to this question has direct relevance for planning optimal instrument suites of future planetary exploration missions. Further, it will help provide context for studies of sedimentary systems on Titan from Dragonfly stereo-imaging data. This task will be integrated with teaching through GeoFORCE, a UT summer internship program for high school students from marginalized communities. Field visits will be incorporated into a GeoFORCE module, with students helping to collect, process, and analyze the data for this locally relevant site.

Laura Kerber/Jet Propulsion Laboratory
Improving Science/Engineering Communication

As a research scientist at the Jet Propulsion Laboratory, my career sits at the intersection between science and engineering. In addition to pursuing pure research, my role is frequently as a representative of the planetary science community among engineers and technologists building missions and developing technology for future missions. The Early Career Award would allow me to advance my career goal of participating in engineering efforts in a way that maximizes their usefulness to the planetary science community. To do this, I propose to develop a series of lectures and targeted field experiences designed to cultivate both knowledge and passion for planetary science amongst early career engineers. These efforts will provide professional development opportunities for myself to improve as science/engineering liaison and prepare for project science and principal investigator roles. They will also open new field areas for my scientific research and allow the collection of pilot data sets that will serve as the seeds for future grant proposals both for pure research and technology collaborations. Overall, the tasks described in this proposal are designed to help the planetary science community by improving communication and understanding between scientists and engineers.

Juan Lora/Yale University
Disseminating the Science of Planetary Atmospheres and Climates

Insights gleaned from investigating the diversity of atmospheres outside our planet provide a glimpse of the range of possible atmospheric conditions; understanding the processes that underpin the behavior of planetary atmospheres corroborates our understanding of our own. PI Lora leads the Planetary Atmospheres and Climates

Laboratory (PAC Lab) group at Yale University, and is working to build up the group's capabilities and visibility, attract and recruit talented students and postdoctoral scholars, and significantly contribute to increasing the group's footprint in science outreach activities, especially with a view toward broadening participation and increasing scientific literacy. We propose a plan to better and more broadly integrate with the scientific community and the public, in parallel advancing the Lab's technical impact and establishing a robust teaching and outreach platform with which to engage the University and local communities. The two proposed activities are to develop and deploy i) a flexible, user-friendly website and public archive for our models, and ii) a multi-tiered platform for teaching and outreach activities. The proposed tasks will accomplish several critical objectives, including i) development of science capability and technical expertise; ii) dissemination of our science results for use by the community; iii) investment in infrastructure for teaching and outreach to permit engagement with various audiences and contribute to advancing science literacy, interest, and participation; and iv) professional development for group members, training future leaders and educators in planetary climate science.

Marisa Palucis/Dartmouth College
Using flume studies to quantitatively assess planetary surface processes and paleoclimate

Objectives: I am a planetary geomorphologist whose research is founded in field-, lab-, and remote sensing-based observations to broadly understand: 1) how is early environmental change on Mars recorded in the landscape, 2) how does terrestrial climate change affect rates and mechanisms of sediment transport, and 3) how can we apply what we learn on Earth to early Mars. These major lines of scientific inquiry are important for determining if Mars ever supported life and how life on our own planet is affected by climate change. They are also tightly coupled, as understanding ancient martian landscapes requires detailed knowledge of how our own planet's surface has evolved under different climactic regimes. Since coming to Dartmouth, I have established a new planetary surface processes research program and provided mentorship opportunities for a diverse community of students interested in planetary science and future NASA careers. While start-up funding has allowed me to build a successful planetary GIS lab (where we have trained multiple graduate and undergraduate students from Dartmouth and other local universities), with the Planetary Science Early Career Award, I plan to establish a robust planetary sediment transport lab, also intended for the larger planetary community. Methodology: Within my research program, I incorporate a diverse array of tools and techniques, including: surficial mapping, hydrologic measurements and modeling, sedimentology and sediment transport, remote sensing, and large-scale laboratory experiments. A key outcome from the ECA would be the construction of two novel flumes within my existing sedimentology lab. One is a rotating drum flume, which can be used to understand gully incision of crater walls, debris flow and mudflow mechanics, and particle abrasion mechanisms. The second is a steep tilting flume, which can recirculate both sediment and fluid, and can be used to study granular avalanching, mass flow processes, and traditional river transport. The development of these novel flumes will allow my group and others in the planetary community to perform sediment transport experiments under conditions relevant to planetary landscapes and determine how well our earth-based sediment transport models work under extraterrestrial climates and fluid rheologies. I also intend to use ECA funds to support my URM graduate students so that these students' interests, commitments, and abilities will persist within the NASA workforce and planetary science community. Relevance: My research is fundamentally linked to the goals of NASA's Planetary Science Division, especially regarding understanding the history of Mars' surface water and the fate of the planet's climate (2013-2022 Decadal Survey). My work is relevant to (1) NASA's Solar System Workings program, namely Evolution and modification of surfaces" and the need to Develop theoretical&bases for understanding features in the context of the varying conditions through time after formation" and (2) the Mars Data Analysis Program, as my group uses previously released mission datasets (i.e., Mars Global Surveyor, Mars Express, Mars Reconnaissance Orbiter, Mars Odyssey, Mars Science Laboratory, the Mars Exploration Rovers, and Mars 2020) to improve our understanding of the timing and global extent over which surface water existed on Mars.

Richard Remsing/Rutgers University, New Brunswick
Uncovering the Molecular Mechanisms of Protocell Membrane Formation and Stability

The ultimate goal of the proposed research is to build a fundamental understanding of the molecular mechanisms that drive the formation and stability of primitive, protocell membranes. We will specifically focus on uncovering how interactions between fatty acids and mineral surfaces can drive membrane formation and how membrane interactions with prebiotic amino acids and ions impact membrane stability. This will be achieved by combining molecular simulations and statistical physics-based theories. The results of this work will provide important molecular-scale insights into how compartmentalization can originate in early Earth environments. Quantifying lipid mineral interactions and determining which interactions favor membrane formation will help narrow down the vast inventory of mineral surfaces that may be relevant to the origins of life. Similar insights will be provided by investigating the interactions between prebiotic amino acids and protocell membranes. The proposal will expand my research directions to membranes and their interfaces, while leveraging my experience in modeling mineral surfaces and their interactions with aqueous solutions to create atomic-scale insights into prebiotic compartmentalization processes. A key step in the origin of life is compartmentalization the formation of primitive membranes that encapsulate and concentrate important prebiotic polymers, eventually forming protocells, and this work seeks to provide molecular insights into how this can be templated my mineral surfaces. Therefore, this work is responsive to the "Prebiotic Evolution" heading of the "Exobiology" (C.5) solicitation, because it seeks to understand molecular processes that govern the prebiotic evolution of materials necessary for life, and the conditions in which these molecular processes can occur. Because of its potential to narrow down the inventory of prebiotically-relevant minerals, this proposal is also relevant to the "Biosignatures and Life Elsewhere" heading of the above solicitation. The Planetary Science Early Career Award will be used to fund a graduate student and undergraduate student researchers from diverse socioeconomic backgrounds, with an emphasis on funding first generation undergraduate students throughout the summer months and the academic year, enabling undergraduate research experiences that would otherwise be impossible in the usual research-for-course credit system. This has the goal of training and promoting diversity in the next generation of skilled, technical workers in exobiology, and in the physical sciences more broadly. The training components of this proposal are responsive to NASA's Strategic Goals, specifically 4.4, as well as NASA SMD's Priority 4, "Inspiration."

Development and Advancement of Lunar Instrumentation
Abstracts of Selected Proposals
(NNH21ZDA001N-DALI)

Below are the abstracts of proposals selected for funding for the Development and Advancement of Lunar Instrumentation program. Principal Investigator (PI) name, institution, and proposal title are also included. 44 proposals were received in response to this opportunity. On January 6, 2022, five proposals were selected for funding.

Lance Christensen/Jet Propulsion Laboratory
Water Isotope Tunable Laser Spectrometer

In situ quantification and isotopic characterization of lunar water are high value targets for NASA and future commercial deployments. The suspicion that permanently shaded regions of the Moon could be home to large amounts of water ice that function as both witness plates to the evolution of the solar system and as potential resources for fueling human exploration dates back decades. However, confirmation of their presence has been elusive due to technical challenges accessing and making measurements in these regions. As the next round of lunar exploration begins with the Artemis program, we can take advantage of advancements in instrument miniaturization and increased robotics capability to enable these measurements.

We will develop a water isotope tunable laser spectrometer (WITLS) to measure water abundance and isotopic ratios on the lunar surface. These in situ measurements will inform on the distribution, origin, and processes affecting lunar water. By focusing on water, instrument size can be reduced to hundreds of grams requiring only micrograms or less of sample. By being miniature, less resources are needed for operation, more payload room is available for other systems, and greater integration flexibility into other form factors such as hand-held sampling tools is possible. Such in situ measurements can be performed during collection of material slated for sample return and thus WITLS performs a key Artemis Science Definition Team goal of volatile monitoring.

Peter Gorham/University of Hawaii, Honolulu
Flight Receivers for Orbital Remote Sensing of Buried Lunar Ice Deposits via CoRaLS: the Cosmic Ray Lunar Sounder

We propose to develop the technology readiness of the critical receiver system that is central to CoRalS: a sounder for extensive ice deposits in the lunar regolith using the radio signals produced by ultra-high energy cosmic rays incident on the surface of the Moon. While extensive ice deposits have been found in the permanently shadowed regions (PSRs) of Mercury, only traces of water ice have been found on the surface of lunar PSRs, and active radar measurements sensitive to the top meter or so of regolith show no clear signal yet from extensive deposits. Given expectations from impact gardening, the extensive ice deposits on the surface of Mercury are expected to be recent (<10 Myr), suggesting that their source is sudden and voluminous. These considerations leave the possibility for relic extensive ice deposits below the first meter of regolith provided that a sudden and voluminous source, similar to Mercury, emplaced ice within the last Gyr. The CoRaLS mission will complement active radar by probing depths well below the first meter, using a known source of coherent radio impulses that are effectively implanted into the regolith.

Mihaly Horanyi/University Of Colorado, Boulder
Lunar Meteoroid Monitor (LMM)

We propose to develop and advance the flight technical readiness level (TRL) of the Lunar Meteoroid Monitor (LMM) instrument to measure the flux, size and speed distributions, and directions of the meteoroids bombarding the lunar surface. These measurements have both scientific and technical importance supporting lunar explorations, including contributions to the development of dust impact hazard mitigation strategies for crewed and robotic missions to the Moon. Meteoroid impacts play a critical role in sustaining the tenuous lunar atmosphere and providing the delivery, transport, and loss mechanisms for volatiles that are also relevant for in situ resource utilization. The Lunar Ejecta and Meteorite (LEAM) experiment, placed on the surface during the Apollo 17 mission, most likely was swamped by slow-moving highly charged lunar fines. In addition, LEAM struggled with thermal issues and it could not be operated during the lunar day. The proposed LMM instrument will provide the capability for the long-term continuous monitoring of meteoroids bombarding the lunar surface.

The proposed LMM is a large surface area dust impact detector utilizing thin Polyvinylidene Fluoride (PVDF) films. PVDF-based dust detectors have an excellent record in space applications, including instruments onboard the Giotto mission to comet Halley, Cassini to Saturn, New Horizons to Pluto, and the AIM Earth-orbiting satellite. This proposal is for the development of: a) a deployable structure to enable a large detector area while providing a compact configuration for stowing through launch; b) a low-power electronics for signal processing that will enable the use of LMM through the lunar night; and c) a thermal design to enable the safe operations of LMM during the lunar day (when temperatures can reach above 120 C) and night (when temperatures drop below -170 C).

William McDonough/University of Maryland, College Park
PLASMA: Pulsed Laser Ablation Sampling and Mass Analysis

The chemistry of lunar materials, including surface and deep interior samples, record local, regional, and global scale processes and provide spatial and temporal context to the evolution of the Moon and the origin of economic mineral resources. Previous efforts to model the composition and internal structure of the Moon have come from the Apollo missions, laboratory studies of return samples, and orbital-based remote sensing. However, limitations exist to these methods, and new questions continue to emerge. The abundance and distribution of trace elements (ppmw-levels) coupled with radiometric systems (e.g., Rb-Sr) may hold the key to unlocking the Moon s secrets.

The community has identified multiple broad science goals that can be accessed via trace element systematics and radiometric chronology (Scientific Context for Exploration of the Moon, 2007), including:

- The bombardment history of the inner solar system revealed from the Moon
- The structure and composition of the Lunar interior
- Lunar volcanism as a window into the thermal and compositional evolution of the Moon

In addition, NASA Planetary Science Decadal Survey (Visions and Voyages, 2011) identified the critical science questions regarding the geologic history and chemical evolution of rocky planetary bodies to understand:

- (Building New Worlds) - What governed the accretion, supply of water, chemistry, and internal differentiation of the inner planets?
- (Solar System Workings) - How have the myriad chemical and physical processes that shaped the solar system operated, interacted, and evolved over time?

Here, we propose to construct PLASMA, a miniature laser ablation (LA-) inductively coupled plasma mass spectrometer (ICPMS) to enable in situ measurements of trace elements in lunar surficial deposits. The LA-ICPMS technology developed here can analyze quantitatively the abundances of nearly every element in the periodic table (Li to U), including trace levels of long-lived radioactive elements (K, Th, U) that control the Moon s heat flux, as well as critical metals of value to human exploration objectives, such as the first-row transition elements (Sc through Zn) and rare earth elements. Further, the mass spectrometer is equipped with a collision cell that enables access to Rb-Sr chronometry. The constraints provided by these analyses address the high priority objectives of the community, while enabling insights into the chemical heterogeneity and thermal history of the Moon.

Rebecca Schindhelm/Ball Aerospace & Technologies Corporation
Revelio: An autonomous High Dynamic Range Camera for Polar Science and Exploration

The lunar poles are highly desirable target regions for both science and exploration, and are the focus of many recently discussed LDEP mission concepts. Due to low solar elevation and the resulting extremes between lighted and shadowed regions, the terrain surrounding a landing site would present scenes with a large range of radiance in the visible wavelengths. Some science missions objectives involve travel into permanently shadowed craters. This variety of lighting conditions requires an imager that can represent these extremes in a single radiometrically accurate image. In addition, due to the short nature of some of these missions (~14 days), a high degree of autonomy is necessary to minimize the time of humans in the loop. An ideal visible imaging sensor would accommodate all these factors while minimizing size, weight, power, and data volume, in order to prevent dominating requirements for a mission concept of operations.

We propose to qualify a prototype visible wavelength camera combining a sensor with high dynamic range, low light level sensitivity, and autonomous code for controlling gain levels and exposure time. Ball Aerospace has developed a breadboard camera leveraging heritage and design from previously flown space cameras. The Revelio camera offers the user the ability to select from specified gains settings, or from autonomous gain control modes. One autonomous mode is real-time automatic gain and exposure control (AGEC) to prevent saturation in selected image regions. Another autonomous mode selects optimal gain, on a pixel-by-pixel basis, from images acquired in rapid succession. We will build a camera brassboard prototype designed to meet requirements of a lunar polar science mission and subject it to environmental (thermal vac, vibration) testing and radiometric calibration. This will result in a TRL 6 prototype ready to propose to a flight mission.

Revelio would enable characterization of morphology in shadowed regions on centimeter scales in the near field. Local maps could provide context for LROC NAC measurements on a global scale. Color imaging would allow characterization of surface properties via Hapke modeling at high spatial resolution. Revelio would also complement thermal imager data by providing an independent measurement of incident solar flux. In a shadowed region, Revelio data could be combined with Far-Ultraviolet data for consistent determination of regolith porosity or presence of ice. Finally, a rover exploring shadowed regions could utilize the AGEC algorithms to optimize real time characterization of nearby scenes without needing an active sensing system.

Hot Operating Temperature Technology Program
Abstracts of selected proposals
NNH21ZDA001N-HOTTCH

Below are the abstracts of proposals selected for funding for the Hot Operating Temperature Technology Program. Principal Investigator (PI) name, institution, and proposal title are also included. 38 proposals were received in response to this opportunity. On November 16, 2021, 7 proposals were selected for funding.

Chen Cheng-Po/General Electric Company

High Temperature UV near field Imager

GE Research, in collaboration with NASA Glenn Research Center and Ohio Aerospace Institute, proposed to design, fabricate, and test silicon carbide (SiC) electronic components to demonstrate an ultraviolet (UV) near-field image camera operating in high-temperature environments up to 500°C for imaging geological samples on the surface of Venus. The SiC imager will be sensitive to UV light from a powered source and will use either reflected light or fluorescence from surface geological formations. The target operating environment is 500°C for 60 days with image resolution of 1 mm per pixel at 0.5 m distance. The team will design and build multiple size arrays up to 32x32 pixels per die, with scalable architecture such that multiple dies can be used to build larger arrays. The proposed project will move the SiC PD array to TRL5 by changing fabrication materials, modifying device structure, and testing to demonstrate utility and durability.

Grandidier Jonathan/Jet Propulsion Laboratory

Venus Surface Solar Array

NASA's roadmap for Venus exploration has identified long-lived landers as one of the key mission types for the next decade. Such missions will require a power source that can operate in the harsh Venus surface environment for an extended period. The environment includes high temperature, low solar irradiance, high pressure and high corrosion. State-of-art power sources such as radioisotope thermoelectric generators, primary batteries or solar arrays are not suitable for long duration Venus surface missions due to their poor performance in the relevant environment. Because of this, only short-duration Venus surface missions of a few hours have been implemented so far. The goal of the proposed effort is to develop a solar array that can operate in the Venus surface environment and provide power to a lander for a period of at least one solar day (two Earth months).

In a prior HOTTech-sponsored effort, we established the technical feasibility of solar cells optimized for low irradiance, high temperature (LIHT) environments, and demonstrated their operation for up to 49 days at 465°C. The current proposed effort will build upon these results and mature the technology to the level where it can be infused into flight projects. We plan to advance the Venus surface solar array from TRL3 currently, to TRL5 upon completion of the project. The Venus surface solar array will be a fully integrated assembly comprising solar cells, interconnects, mechanical structures, optical components and wire harnessing, and capable of directly interfacing with other assemblies in the power subsystem. Importantly, the array will be able to withstand the high-temperature, high-pressure and corrosive atmosphere, while protecting the solar cells from corrosion degradation.

The objectives of this proposal are: 1) Optimize the LIHT cell fabrication processes to achieve ≥ 3.4% average population efficiency at a temperature of 500°C, under a red-shifted spectral irradiance of 89.4 W/m2; 2) Design and fabricate a ~10 cm x 10 cm solar panel test article, representative of one module of a full size, flight-like solar array, and capable of stable operation under Venus surface temperature, pressure and corrosion conditions; and 3) Demonstrate through test a ≥ 2 W/m2 power output at the array level under Venus-surface temperature and irradiance conditions, and ≤ 20% degradation after exposure to the relevant temperature, corrosion and pressure environments for a period of ≥ 60 days.

Kremic Tibor/NASA Glenn Research Center

High-Temperature MEMS based Venus seismometer

The objectives of the proposed work are to design a micro-electromechanical system (MEMS) sensor based seismometer that, when fully matured, will be able to operate on the Venus surface for >60 days and to develop the seismometer to a maturity level of at least TRL-4 by the end of the project.

This project will leverage progress and expertise acquired through several other NASA funded efforts. The scope of this work will be to; a) adapt seismic sensors (with heritage from prior space missions) to the Venus environment, b) design & build the supporting high-temperature electronics to acquire, condition, and process the sensor's measurements via iterative building process, c) integrate a) and b) into a 1 axis system that could interface with a notional long duration lander d) test the system for environmental robustness and performance, e) support elements a - d with the requirements definition, analysis, modeling and testing to provide confidence that the instrument will have an acceptable noise floor across a relevant frequency band for Venus.

Mumm Erik/Honeybee Robotics, Ltd.

A Venus Durable Actuator and Electronics System

Venus surface conditions are exceptionally challenging for the use of surface platforms due to the 460°C, 91 atmosphere caustic Venus surface environmental conditions. Thus, the HOTTech II goal is "to develop and mature technologies that will enable, significantly enhance, or reduce technical risk for in-situ missions to high-temperature environments with temperatures of 500 degrees Celsius or higher for a period of at least 60 days". Such missions must be tailored for operation in the Venus surface environment and include technologies viable for operation in such conditions. For example, the most viable proposed mission for long-lived 60 day Venus surface operations is the Long Lived In Situ Solar System Explorer (LLISSE) including, e.g., meteorology and chemical species measurements based in part on advances in Silicon Carbide (SiC) electronics. Further, LLISSE is a lander platform from which a range of missions can be accomplished upon the introduction of appropriate science enhancing technology and capabilities, e.g., a Venus durable seismometer. Other technologies can also provide increased capabilities and improved science to such a platform.

Honeybee Robotics, NASA Glenn Research Center, and OAI propose the development and demonstration of a Venus Durable Actuator and Electronics System specifically tailored for lander platforms such as LLISSE. This is a smaller actuator system scaled to provide functionalities such as deployment of a seismometer, windmill power generation, a robotic arm for sample examination, or a positioning motor system. In particular, as an example application, this actuator system targets compatibility with the Venus In-Situ Surface System Imager (VISSI) under development in PICASSO. VISSI is OAI led and modeled after the imaging system of the Viking Mars lander cameras with a low-bandwidth, linear array, scanning platform capable of gradually building up a high resolution panorama of a landing site for extended durations on the Venus surface. The emphasis of VISSI is on SiC electronic circuits, optical detectors, and components with limited development of an actuator system; this proposal provides such an actuation system with an approach and material selection appropriate for 60 days of Venus surface operations. In conjunction with this actuation system development, we will leverage significant high-temperature, harsh environment expertise in designing and fabricating SiC based electronic circuits that are able to function stably in the uncooled, ambient Venus surface environment. The core electronics have already shown durable operation in simulated Venus surface conditions for 60 days with a range of signal conditioning, data processing, power management, and communication circuits in development. Related to this actuator system in HOTTech II, we will leverage on-going development of a simple SiC based microprocessor and Bipolar Junction Transistors for power applications to provide a control capability for the Venus actuator system. The combination of actuation and SiC electronics will be used to demonstrate the capability to perform rastering of a photodiode array structure in the pattern of the Viking Mars lander cameras in simulated Venus surface conditions for 60 days. This proposal is responsive multiple aspects of the HOTTech II call including Actuators/Motors, Imaging Cameras, Low-Power Electrical Circuits, and to a lesser degree Power Transistors. This proposal combines leaders in Venus relevant technologies to produce a new enabling capability: long term Venus durable actuation with electronic control suitable for smaller lander platforms such as LLISSE. This technology will be targeted towards imaging applications during the HOTTech II project, but is applicable to a range of other applications and functionalities in need of basic actuation. Thus, this proposal has broad science impact across a range of mission scenarios for long lived Venus surface applications.

Neudeck Phil/NASA Glenn Research Center

Non-Volatile, Low Power, and High Density SiC Memory For Future Venus Missions

The Hot Operating Temperature Technology 2021 Program goal "is to develop and mature technologies that will enable, significantly enhance, or reduce technical risk for in-situ missions to high-temperature environments with temperatures of 500 degrees Celsius or higher for a period of at least 60 days" including "Low-Power Electrical Circuits (<1000 mW)". One major technology gap for long term Venus surface exploration is low-power high density digital memory. This proposal directly addresses this notable technical challenge.

The proposed work will seek to develop and demonstrate 500 °C durable Non-Volatile Random Access Memory (NVRAM). The SiC JFET-R NVRAM is planned to be capable of storing mission-relevant data for hours at Venus surface temperature (460 °C) even in the complete absence of any power supplied to the chip. Similar to their low-T silicon memory counterparts, the SiC NVRAM would only require power for active reading and writing operations, and perhaps (worst case) "stored content refresh" operations taking only a second or two of power for every hour or two sitting on the surface of Venus. Averaged over time, the NVRAM approach will permit more than 1000-fold reduction power for each bit over the present state-of-art 500 °C durable RAM approach. Furthermore, we will migrate the SiC JFET-R process towards stepper-based lithography that will enable additional 4-fold size reduction in chip area of each bit/cell.

The Resistive Switching Device (RSD) approach has proven practical for silicon memories, including high temperature NVRAMs operated up to 300 °C (temperature-limited by the silicon semiconductor). In the first half of the project, we will systematically investigate RSD's made from Venus-durable materials and processing towards directly leveraging them into the proven 500 °C/Venus-durable NASA Glenn SiC JFET-R process flow. During the second half of the project, we will seek to implement a complete 500 °C durable SiC NVRAM chip with 1 kilobit storage capacity with total average power below 20 mW.

Ohodnicki Paul/University Of Pittsburgh

Advanced Co-Based Nanocrystalline Soft Magnetics for Extreme Temperature Inductor Applications

As active semiconductor devices realize high temperature capability, advances in passive electronic components (inductors, capacitors, and resistors) become increasingly important. For inductive components demonstrations are lacking for magnetic materials capable of extended operation at T=500C+ at high switching frequencies (f>~1kHz) relevant for power dense electric motors, transformers, inductors, and magnetic sensors. The proposed program addresses this gap through magnetic materials and manufacturing research, focused on newly developed and patented Co-rich based nanocrystalline alloy systems, complemented by inductor device design and demonstrations also leveraging the latest advances in high temperature packaging and windings. At program start, high temperature inductor technologies are estimated at Technology Readiness Level (TRL) of 3 based on early proof of concept studies by project partners. At program conclusion, TRL of 5 is estimated based on testing in application relevant conditions with a clear path to further maturation and near-term commercialization through strategic partnerships with a commercialization partner (CorePower Magnetics), an end-user (Raytheon), and NASA. Capabilities and limitations of existing soft magnetic alloys for high temperature surface planetary exploration missions will also be clarified to guide future research.

Specifically, we propose to benchmark existing soft magnetic materials for NASA HOTTech high temperature operation under relevant testing and environmental conditions while pursuing new soft magnetic nanocrystalline alloys, advanced manufacturing methods, and component designs to enable high frequency inductive components for T=500C+ high temperature electronics. The program seeks to accomplish the following objectives targeted for NASA HOTTech operational requirements of T=500C for at least 60 days:

Objective #1: Benchmark material and magnetic property stability after exposure to simulated 500C Venusian atmosphere at NASA Glenn Extreme Environment Rig (GEER) for commercial bulk crystalline (FeCo-,FeSi-,FeCr-based), and existing nanocrystalline (FeCo-,Co-based) alloys.

Objective #2: Develop new high temperature optimized nanocomposite alloy chemistries and demonstrate capability for high temperature stable permeability engineering of magnetic cores through advanced manufacturing techniques that include both field and tension annealing.

Objective #3: Design and fabricate prototype inductors based upon existing commercial and state of art alloys, as well as with newly developed nanocomposite alloy systems, leveraging commercial advances in packaging, thermal management, and insulating windings. Demonstrate successful operation of high temperature inductors in application relevant excitation conditions.

To successfully accomplish stated objectives and enable rapid commercial adoption of developed technologies, a combined academic (University of Pittsburgh), industry (Raytheon Technologies, CorePower Magnetics), and NASA laboratory integrated research team has been assembled to leverage on-going efforts, established capabilities, and domain specific expertise. In addition to space applications these high temperature materials and inductors are also relevant for hybrid-electric propulsion and Air Force power electronics applications.

Sadwick Laurence/Innosys, Inc.

A High Temperature Transmitter for Venus Surface Environment

The objective of this proposal is to develop and demonstrate a scalable UHF-band transmitter capable of operation in extreme high temperatures and pressures in hostile and corrosive environments of Venus, Mercury and interior of gas giants. The transmitter development/ demonstration will be carried out by InnoSys, Inc. and JPL using InnoSys' Solid State Vacuum Devices (SSVD), which are termed solid state devices due to the microfabrication of the triode or transistor within the vacuum. For the last 20 years, InnoSys has developed SSVD based power amplifiers and voltage-controlled oscillators (VCOs) for commercial/government customers. Internal SSVD elements and devices are capable of operating at temperatures that far exceed any semiconductor device. Vacuum packaged SSVD triodes have been proven to operate reliably in >500 C and extreme high radiation environments with no measurable change in performance. Additionally, they have been shown to survive the shock and vibrations experienced in a missile launch and have been proven to operate over an 8+ decade range of vacuum from ultrahigh vacuum (UHV) to 10-3 Torr H2 and Helium (He) with no adverse effects. The SSVD coupled with microwave planar high temperature passive components will be used for the transmitter development. The transmitter will operate without additional environmental protection in Venus surface ambient conditions and will have power consumption <90W, operating frequency >300MHz within UHF-band, output power >30W, and bandwidth >1MHz. Although vacuum packaged SSVDs have demonstrated extreme environment survivability, they have not been tested within the corrosive gasses or high-pressures of Venus surface conditions. Risks associated with environmental exposure include diffusion through the enclosure and corrosion of enclosure materials leading to possible loss of vacuum. The risks will be addressed through design (using materials known to survive exposure), modeling, environmental exposure (passive and active), and post-exposure evaluation. For the last 20 years, InnoSys has used as primary packaging material ceramics proven by others to be compatible with Venus' surface. One area of focus will be on metal seals and electrodes for the packaged transmitter. As long as the enclosure is able to maintain acceptable vacuum within the package, the internal electronics are only exposed to elevated temperatures. To address issues associated with temperature dependent changes in capacitance and inductance, we will use vacuum capacitors and vacuum core inductors. The complete oscillator, modulator, power amplifier and associated passives that constitute the transmitter circuits will be designed for operating multiple years. To achieve a transmitter with an operational life of 60 days or longer, we will focus on the following activities: (1) Design and fabrication of packaging enclosure, and testing of the fabricated packaged SSVD inside the vacuum sealed packages, at 500 C in air, at 500 C and 92 bars (CO2) and finally emulated Venus environment in the NASA Glenn Research Center (GRC) Glenn

Extreme Environments Rig (GEER). (2) In parallel, the SSVD based transmitter circuit will be developed by InnoSys and tested at 500 C. The packaged test articles and transmitter will be evacuated to UHV and continuously heated to 600 C with an exterior pressure of 4000 Torr He for 6+weeks and monitored for residual He levels inside the package before sealing as part of studying the diffusion/permeation of He at 600 C into the evacuated vacuum package. After passing this test, it will be sealed for further testing. JPL will develop software and hardware to verify the transmitter operation in various stages during the process and finally in GRC GEER chamber. During these tests any degradation of the material over time will be characterized and if needed mitigations applied to meet mission requirements. These risk reduction tests will increase the transmitter TRL from current 3 to 6.

Yearly Opportunities for Research in Planetary Defense
Abstracts of Selected Proposals
(NNH21ZDA001N-YORPD)

Below are the abstracts of proposals selected for funding for the Yearly Opportunities for Research in Planetary Defense program. Principal Investigator (PI) name, institution, and proposal title are also included. Twenty-three proposals were received in response to this opportunity. On October 19, 2021, twelve proposals were selected for funding.

Mallory DeCoster/Johns Hopkins University
The Evolution of Shape: Designing the Next Generation Kinetic Impactor for Planetary Defense

Understanding how to deflect an incoming asteroid is of great importance and a focus of research undertaken by the planetary defense community. Deflection of an asteroid by a kinetic impactor is one such mitigation method that has a high degree of technological maturity.1,2 In 2022, NASA s planetary defense mission, the Double Asteroid Redirection Test (DART), will provide the first full-scale technology demonstration of a kinetic impactor.3 However, the DART mission is just a single test of one kinetic impactor design, begging the question: Is it possible to optimize the design of a kinetic impactor to make it the most efficient deflector that it can be? In this proposal, we will explore how to best design the next generation of kinetic impactors. Using high-fidelity hydrodynamic models, we will assess how mass placement within an impactor (e.g., projectile geometry) and a system of multiple kinetic impactors might be optimized to maximize the deflection caused by kinetic impactor technology.

To assess how to best design the next generation of kinetic impactors, we will focus on the following main science questions with specific proposed research tasks:

Main Science Questions:
1. How does the mass placement within a kinetic impactor influence its effectiveness for planetary defense? (Task 1)
2. How does a system of clustered impactors perform compared to a single impactor of the same mass? What are the advantages and disadvantages of this concept? (Task 2)
3. To what extent can answers to #1 and #2 be used to achieve higher efficiency kinetic impact deflection, given constraints on spacecraft design? (Tasks 1 & 2)

Proposed Research Tasks:
1. Use numerical models to assess the effects of mass placement on the deflection caused by a kinetic impactor.
2. Perform numerical simulations of a system of clustered projectiles to compare their deflection effectiveness to that of a single kinetic impactor.

Relevance:

YORPD encourages proposals that address potential mitigation of NEOs that pose an impact threat . In addition, the National Near-Earth Object Preparedness Strategy and Action Plan includes a goal to develop technologies for NEO deflection and disruption missions. The proposed work will provide insights into how specific kinetic impactor designs affect deflection efficiency and provide a basis for optimizing kinetic impactors in the face of uncertain NEO properties.

Maxime Devogele/Arecibo Observatory
Polarimetry as a tool for physical characterization of potentially hazardous NEOs

The degree of linear polarization of sunlight scattered by an asteroid surface contains valuable information for NASA s goal to characterize a representative sample of NEOs by measuring their sizes, shapes, and compositions, [and to develop] ... mitigation of NEOs that pose an impact threat .

We propose to observe a sample of pre-selected NEOs not only in polarimetry, but also other complementary techniques such as photometry, spectroscopy, and thermal radiometry. These observations will allow us to perform one of the deepest characterizations that can be obtained for individual objects.

The measured degree of linear polarization is strongly dependent on phase angle (i.e. the sun-asteroid-observer angle). To date, the vast majority of asteroid polarization measurements are of main belt asteroids for which the range of available phase angles is limited and rarely exceeds 30°. However, in the case of an NEO, the observable range of phase angles can reach 120°, providing an opportunity for a new mode of analyzing asteroid surface properties.

The properties of the phase-polarization curve of an asteroid are mostly defined by albedo and at second order by the regolith grain size. Numerous calibrations between polarization and albedo have been proposed for main-belt asteroids (i.e for phase angles below 30°). However, these calibrations lack data at larger phase angles, where polarization data can be more diagnostic. We thus propose to calibrate the polarization-albedo, and grain size relationship for NEOs at high phase angles.

This investigation will allow us to actively prepare those observatories with polarimetric capabilities and to develop tools for quick characterization of an impacting NEO, and thus providing rapid diagnostic observations with reliable determination of albedo. With proper calibrations, even one observation, obtained at a high phase angle (>30°), can reduce the size uncertainty of the impactor object by a factor of 5 to 10.

We will make use of two facilities with polarimetric capability. The ToPol instrument at the 1-m telescope from the Calern observatory in France and the FoReRo2 polarimeter at the 2-m Rozhen observatory in Bulgaria. These two facilities are highly complementary and will allow full characterization of phase-polarization curves of our targets. We will also probe for variation of the polarimetric response as a function of rotation, which is diagnostic of heterogeneous surfaces. This technique represents one of the best ways to determine surface heterogeneity. We also plan to dedicate small time for observations of newly discovered objects. Focus will be given to virtual impactors that reach V magnitude < 17.

Full characterization of our targets will be performed to put the polarimetric data into context and to derive relationships between polarization and albedo, taxonomy, and surface grain size. The Trappists (North and South 0.6-m telescopes) and the Lowell Observatory 42 will be used to obtain high precision photometry. The 4.3-m Lowell Discovery Telescope (LDT) telescope will be used for visible and near infra-red spectroscopy. The NASA s Infra-Red Telescope Facility (IRTF) will be employed for thermal radiometry observations. Archived observations from Arecibo, NEOWISE and Spitzer will be analysed to provide additional constraints on physical parameters.

This proposal is relevant to the YORPD program as its main goal is the characterization of NEOs with a particular focus on potentially hazardous asteroids. This work will help to lay the foundation for polarimetry as a new characterization technique relevant to planetary defense.

George Flynn/SUNY College at Plattsburgh
Hypervelocity Impact Measurements on Meteorites: Determining the Momentum Transfer in Cratering and the Disruption Energy

OBJECTIVES: Remote sensing, spacecraft observations, and sample returns demonstrate significant diversity of physical and compositional properties of near-earth asteroids (NEAs) as well as their similarity to various types of meteorites. Itokowa is similar to LL and Eros is similar to H anhydrous ordinary chondrites (OCs), while Bennu and Mathilde are similar to hydrous, CI/CM-type carbonaceous chondrites (CCs) and Ryugu is similar to a desiccated CC. Overlapping craters on Mathilde, inconsistent with modeling using terrestrial rock properties, were attributed to Mathilde s high porosity. Comparison of bulk densities to grain densities of constituent minerals shows many NEAs are porous: 42% for Itokowa, 9% for Eros, 40% for Bennu, 41% for Mathilde, and >50% for Ryugu. Laboratory experiments demonstrate porosity affects response to hypervelocity collisions: speed of crater ejecta decreases, depth of crater penetration increases, and energy required for disruption varies with increasing porosity. Meteorites, samples of asteroids, span most of the range of compositions and porosities observed among NEAs. Properties of terrestrial rocks are frequently used in modeling asteroid response to hypervelocity impacts, but Slyuta noted there are no analogues among terrestrial igneous and sedimentary rocks and ores [for the] physical and mechanical properties of the meteorites, or their parent asteroids. We propose meteorite impact experiments to

provide critical starting points for extrapolation to the deflection or disruption of NEAs using size-scaling models in the literature.
METHODS: Properties of meteorites vary significantly from one type to another, but there are general trends. The CCs are systematically weaker and more porous than OCs, with hydrous CCs being the weakest and most porous. We propose to measure physical properties [grain and bulk densities, porosities, unconfined and triaxial compressive strengths, and speeds of sound], and response to hypervelocity impacts [momentum transfer by cratering (B) and threshold collisional specific energy (Q*D)] of six types of meteorites: a low porosity OC, a high porosity OC, a high porosity anhydrous CC, a high porosity hydrous CM CC and both low and high porosity hydrous CI CC simulants. When coupled with our published results on Northwest Africa (NWA) 869, an intermediate porosity OC, and NWA 4502, a lower porosity anhydrous CC, the new results will span most of the porosity, composition and physical property ranges of NEAs.
Kinetic impact deflection is a viable mitigation strategy for a small, solid asteroid. Both B and Q*D are important in understanding the requirements for either kinetic deflection or disruption into fragments too small to cause major damage of an asteroid on a collision course with the Earth. Our preliminary work comparing NWA 869 to NWA 4502 showed the maximum change in velocity (Vm) from a single kinetic impact that results in cratering without fragmentation was an order-of-magnitude larger for the OC than the CC of the same mass. Further measurements on meteorites of other types and porosities required to understand the maximum Vm for other types of NEAs. In addition, we found B values about 3x higher for serpentine and montmorillonite, the two hydrous minerals dominating in hydrous CCs, than for anhydrous targets of the same porosity. The proposed measurements on a hydrous CC and the simulants, required since CI meteorites are rare and too small for this work, will identify the effects of hydration on impact response.
SIGNIFICANCE: There are significant differences between most published hydrocode modeling of asteroid response to hypervelocity impact and results obtained in laboratory experiments on meteorites. We will perform hydrocode modeling of our impacts. Our effort to model the specific targets we impact will provide a better understanding of the physical parameters critical to development of valid hydrocode models for asteroid deflection.

Matthew Holman/Smithsonian Institution/Smithsonian Astrophysical Observatory
Propagation and fitting of artificial satellites orbits to reduce NEO false positives.

In recent years, some of the NASA-funded wide-field NEO surveys have extended their searches from objects with sky plane rates of motion as fast as a few degrees per day to rates of tens to hundreds of degrees per day. This has resulted in the discovery of many smaller and nearer NEOs. Unfortunately, this has also significantly increased the number of false positives from Earth-orbiting artificial satellites, as the rates of motion of those in high-Earth orbit can overlap those of NEOs.

The NEO search, follow-up, and characterization community would like to remove artificial satellites from the data stream as quickly as possible to avoid wasting limited telescope resources. If the observations of a candidate NEO are seen to coincide with the predicted sky plane position and rate of motion of a known artificial satellite, no further observations are needed. Without such an identification, additional observations are required to distinguish an artificial satellite from a natural object.

The primary challenge for identifying known artificial satellites is that their Keplerian orbits change on relatively short time scales, due to radiation pressure, Poynting-Robertson and atmospheric drag, the gravitational perturbations of the Moon, and the gravitational harmonics of the Earth, as well as other unmodeled accelerations. In addition, some are specifically maneuvered by onboard thrusters. The orbits of satellites quickly grow stale if they are not regularly updated to match current observations.

There is only one publically available, open source package for identifying artificial satellites from a catalog of orbits: sat_id, written and maintained by Bill Gray. This code is widely used and is quite effective. However, it has some limitations. First, the author has no ongoing obligation to support the code. Second, when the code is updated, it is often done so in ways that change the input and output signature, without notifying users. Third, the code is not easily altered. Finally, the package is only as good as its catalog of orbits.

We propose to develop a new package for the fitting and propagation of artificial satellite orbits. This package will be built within the framework of the REBOUND/REBOUNDx (Rein & Liu 2012, Tamayo & Rein 2020) orbit integration package, using the IAS15 numerical integrator (Rein & Spiegel 2015). We will include all the relevant terms mentioned previously. We will test the method using archival astrometric observations of artificial satellites.

Once the method is developed and tested, we will develop and maintain a catalog of artificial satellite orbits to be used to identify these objects in astrometric observations. This package will be shared with the full NEO community, so that it can be applied to observations both before and after they are reported to the Minor Planet Center.

This project has the potential to improve the identification of artificial satellites among the data collected by the Planetary Defense Community, thereby reducing the amount of telescope time wasted by unnecessary follow up observations. This is directly relevant to the YORPD objective of improving the operational efficiency of NEO searches.

Joseph Hora/Smithsonian Institution/Smithsonian Astrophysical Observatory
Characterization of Near-Earth Objects using Spitzer NEO Program Data

The goal of this program is to obtain more precise and reliable albedos and diameters for the 2224 NEOs observed by Spitzer in order to refine our picture of NEO compositions, origins, and evolutionary histories. The data were taken over ten years and multiple Spitzer programs, and the catalog of physical parameters we produce will be the first complete and systematic reduction and analysis of such a large uniformly-observed Spitzer sample. It is enabled by gathering all the near-IR light curves, and by use of the latest version of the refined calibration to obtain improved photometry. The resulting catalog will more than double the current number of publicly-available NEO lightcurve measurements and IR-determined diameters and albedos, and enable us to refine models of their compositions, origins, and evolutionary histories. The Spitzer dataset enables these goals in a way that other observatories such as NEOWISE and optical observations alone cannot, although we use those data as available. First, the long Spitzer observation periods permit light curve measurements; secondly, the astrometric accuracy helps to pinpoint locations for deriving orbital parameters; third, Spitzer is more sensitive in the thermal IR than NEOWISE because of the larger aperture and longer integration times, and could observe fainter and therefore more small diameter objects; and fourth, Spitzer's location offered a unique viewing angle to observe NEOs not visible from near the Earth then or in the near future.

This proposal directly addresses several of the objectives in the YORPD call section 1.2 NEO Science: "Analysis of NEO data from spacecraft missions (e.g., NEOWISE, Spitzer, HST, TESS) and from ground-based telescopes (e.g., NASA s Infrared Telescope Facility), which reside in NASA or other public archives (see Section 3.1) with the goal of finding previously undiscovered NEOs, finding pre-discovery detections for extending astrometric arcs of NEOs, and/or determining NEO physical characteristics, and not appropriate to other NASA research programs" and "Archiving and analysis of unarchived legacy NEO survey and follow-up data with the goal of finding previously undiscovered NEOs, finding pre-discovery detections for extending astrometric arcs of NEOs, and/or determining NEO physical characteristics .

Peter Jenniskens/SETI Institute
An orbital element survey of near-Earth long-period comets.

Objectives: This proposal is to survey the population of long-period comets that pass close to Earth orbit from the record of their meteoroid streams. That record documents the presence of comets with orbital periods in the range 250 to 4000 years. We will continue ongoing low-light video observations to discover new transient meteor showers. We will investigate how the measured dispersions of orbital elements relate to the age of the streams and the size of the parent body. For cases where the comet might be on its way in, we will search for long-period comets along the projected path on the sky of the observed meteoroid streams in order to find at least one comet and gain practice with such dedicated searches and demonstrate feasibility as an early warning effort.

Methods/techniques: We will maintain and expand on a global network of low-light video cameras called "CAMS", built to triangulate +4 to -5 magnitude meteors at high precision and measure the orbital elements of these meteoroids. During the course of this program, we will monitor the sky for irregular showers from long-period comet dust trails that wander in and out of Earth orbit. We will mine an existing database of over 2 million meteor orbits for meteor showers of long-period comets, determine their median orbital elements, particle size distribution and dispersions. We will run and further develop existing models for meteoroid stream evolution and apply those to the detected streams to determine their age. We will develop and execute an observing program to search for comets in dedicated observations. The survey strategy will consider that LSST is expected to come online in the first year of this program.

Perceived significance: NASA is chartered to find all asteroids and cometary nuclei that can approach Earth orbit, but those in long period orbits are not observed prior to their impact trajectory in regular survey programs. Nearly all such comets have nucleus sizes above the 340-m size limit. The proposed work will provide NASA with a catalogue of long-period comets with 250 - 4000 year orbits that still need to be found, as well as provide practical experience with doing dedicated searches for the parent bodies in order to demonstrate increased warning time between discovery and potential impact.

Vishnu Reddy Kanupuru/University Of Arizona
CHAOS NEOs: CHAracterization of Small NEOs

Impacts due to near-Earth Objects (NEOs) can have a devastating effect on life here on the Earth. The most recent testament to this is the Chelyabinsk meteor, which on February 15, 2013, disintegrated in an airburst with an energy of ~ 500 kilotons of TNT, injuring hundreds of people and causing widespread property damage in several Russian cities. While ground-based asteroid surveys have been prolific in finding new NEOs and creating an up-to-date inventory, physical characterization of these objects has lagged behind.

The goal of the proposed research is to continue our survey of physically characterizing small NEOs (less than 150 meters in diameter) to constrain their surface composition, rotation state, albedo and size. Additionally, we plan to complement our telescopic survey with laboratory spectral measurements of meteorites to better understand surface properties of small NEOs. We have participated in past IAWN campaigns and demonstrated our quick turnaround characterization capabilities yielding NEO compositions. The proposed research has four main objectives:

1) To determine the rotation state of small NEOs using lightcurves from the MORIS Camera on 3.0-meter NASA Infrared Telescope Facility (IRTF).

2) To compositionally characterize small NEOs, i.e., determine mineral abundances and chemistry, and find meteorite analogs using spectral data from the SpeX instrument on the NASA IRTF.
3) To physically characterize small NEOs and constrain their albedo and diameter using spectral data from the SpeX instrument on the NASA IRTF
4) Obtain laboratory spectral measurements of shock darkened/impact melts belonging to ordinary chondrite and HED meteorite classes to better interpret NEO spectra
Our proposed compositional survey of small NEOs will be the largest of its kind and our laboratory study will be the first spectral dataset of shock darkened/impact melts available to the community.
The survey that is currently in progress (ending in Feb 2021) would characterize 122 of our 242-object sample size and we are requesting five additional years of funding to obtain rotational period and composition of the remaining 120 objects (~25 NEOs/year assuming a 30% weather loss). We used method by Cochran (1963) to estimate the number of NEOs that need to be observed in this size range (absolute magnitude H greater than 20) to obtain a statistically significant result with ~94 percent confidence level.
The PI and his team have more than a decade of a successful track record observing and characterizing NEOs with the NASA IRTF. The photometric data will be reduced and analyzed using an IDL-based code and spectroscopic data will be reduced and analyzed using the Spextools package. The PI has established a spectroscopy laboratory with all the necessary equipment and samples required for this project. The resulting data products will be archived on the PDS Small Bodies Node and the results will be published as DPS conference abstracts and papers in peer-reviewed journals (PSJ).
The proposed research is relevant to YORPD program goal of measuring the sizes, and composition of a representative sample of NEOs, (ROSES 2021, section C.23). In addition, our investigation would utilize ground-based telescopes to develop and demonstrate quick turnaround characterization capabilities yielding NEO compositions, shapes, sizes, and surface properties, which is of interest to YORPD program. Furthermore, our laboratory spectral measurements of shock darkened/impact melts of meteorite samples are within the scope of the YORPD program, which supports laboratory investigations involving meteoritic materials that directly add to the understanding of the physical characteristics of the NEO population .

Paul Sanchez/University Of Colorado, Boulder
Seismic Wave transmission upon impacts on Asteroids

We propose a series of numerical simulations develop a theoretical basis to understand how seismic waves are transmitted on small asteroids, how material parameters such as particle size, particle density, porosity or strength affect the wave-transmission phenomenon and how this can inform us about the strength and internal structure on these bodies.

Specifically, we will focus on the correlation between material parameters and energy deposition as this can be correlated to the crater size and internal structure of asteroids. This work will lay the background for possible approaches to determining the cohesive strength of an asteroid s regolith, its interior porosity and the efficiency of seismic transmission through the body.

The predictions of the models will then be measured against recently published results from sampling and impact manoeuvres of the Hayabusa 2 and OSIRIS-REx mission as well as the detailed information about the crater morphology on their surfaces.

The specific goals of the analysis will be:

1. Study how an impact-produced seismic wave will be transmitted through the surface and interior of an asteroid.
2. Develop models for seismic-wave propagation in granular materials in the asteroid environment.
3. Use the observed morphology of the craters on Bennu and Ryugu to validate the models.
    3.1 Provide a better understanding of the interior of these two asteroids as prototypical rubble pile bodies that are of interest for planetary defence.

Daniel Scheeres/University Of Colorado, Boulder
Long-term dynamical evolution of binary asteroids and asteroid spin states as a probe into their mechanical properties

The proposed research will develop and analyze dynamical models for the evolution of Near Earth Objects (NEOs) over time spans of millions of years. These models will be used to better understand the temporal statistics of NEO flybys of the Earth, and to properly characterize and model the effect of these flybys on the excitation in the spin states of single asteroids and the orbit states of binary asteroids. These models will be able to provide constraints on the relaxation timescales of these bodies. The proposed research has three distinct goals:

1. Develop an accurate statistical model for propagating NEO orbits and close planetary approaches over millions of years.

This time span is essential in order to capture and model several nodal periods of NEO to better understand and predict how the frequency of NEO interactions with the Earth evolve over long time spans. Of necessity, the model will also account for flybys of Mars and Venus, and account for the effects of Jupiter and Saturn on NEO and on the inner solar system planets. The model will be vetted against long-term numerical simulations. It is expected that the frequency of close approaches will vary in a stochastic fashion, leading to periods of frequent flybys followed by long periods of no flybys (or flybys of other solar system objects). This will provide important insight into conditional probabilities of known hazardous asteroids, an ability to predict when asteroids will become hazardous in the future, and to more accurately evaluate when a given NEO may be strongly perturbed by close Earth flybys.

2. Analyze the cumulative effect of flybys on NEO binaries and spin states.

Using these statistical models, we will study what the integrated effect of a period of close flybys may be on given members of the NEO population. If an NEO has a number of flybys of the Earth during one period of time, it is expected to have its spin state excited. However, the degree of the excitation will be a statistical quantity and must be determined through simulation. Similarly, binary asteroid systems will also have systematic effects from a period of close flyby, and can serve as an even more precise probe of these flyby effects, as they are more sensitive to being perturbed by a planetary flyby. Thus, we will also develop a capability to analyze the effect of a series of flybys on binary asteroid systems.

3. Constraints on and Computation of NEO energy dissipation rates.

Arising out of our studies we will draw forth implications for the dissipation properties of NEOs and binary asteroid systems, utilizing results from Objective 2. From the simulations the degree of expected excitation in asteroid spin states and in binary asteroid systems will be modeled and compared to the current spin states and orbits of known NEO binary systems. Again, binary asteroid systems should be an even more sensitive population. However, we note that many binary systems are apparently in a synchronous state, while only relatively few are excited into an asynchronous state. Our analysis will enable us to predict the fraction of binaries that should be subject to excitation, and then by comparison with their statistics place constraints on rates of internal energy dissipation. We will also utilize granular mechanics simulations to model these excited asteroid spin states and binary asteroid systems in order to develop better understanding of this relaxation process.

Edward Tedesco/Planetary Science Institute
Archiving LONEOS NEO Survey Images

Goals and Objectives

The objective is to archive all available images obtained with the Lowell Observatory Near Earth Object Survey (LONEOS) telescope into the Small Bodies Node of the Planetary Data System (PDS-SBN).

The LONEOS surveys (NEO and Lightcurve) used a 0.6-m f/1.8 Schmidt telescope from 1998/07/10 - 2008/03/01 and 2010/01/04 - 2011/06/06, respectively. Most LONEOS images cover 2.88x2.88 deg to a V magnitude of 19.3.

These LONEOS data, based on preliminary information provided by the proposers, are available from https://sbnarchive.psi.edu/loneos/

Approach and Methodology

Both the PI and Project Manager of LONEOS have retired and are unavailable to contribute to the archiving of this data. The LONEOS images were obtained from the project's principal observer, Brian Skiff, and Larry Wasserman, also at Lowell, who provided data recovery and transmission to the Planetary Science Institute (PSI). A census of the available data shows that there are ~317,000 NEO survey images from 945 nights and ~110,000 Lightcurve Survey images from 149 nights.

Python scripts, a number of which have already been created, will generate PDS-compliant Images from these data. Additional metadata files will be created to aid users in searching these images for specified objects or regions of the sky using their own or the PDS/SBN's NEO Survey Search Tool, that allows searchable access to NEO Survey image data archived at the PDS-SBN. We will participate in the peer review of these datasets and resolve any liens that arise to ensure that the final products will be successfully archived.

Relevance

This work is relevant to program element (PE) C.23.1.2 NEO Science bullet 3: Archiving and analysis of unarchived legacy NEO survey and follow-up data with the goal of finding previously undiscovered NEOs, finding pre-discovery detections for extending astrometric arcs of NEOs, and/or determining NEO physical characteristics . This PE is the most appropriate for the work proposed because this PE is specifically for Archiving and analysis of unarchived legacy NEO survey and follow-up data. , which is exactly what we are proposing.

We will make available to the community new data products totaling approximately 427,000 wide-field images (~10 TB). All these images are between 10- and 20-years old. Hence, when the preliminary orbit for a recent discovery predicts it passed through the field of a LONEOS image that image can be searched for a so-called precovery observation . If found, that object s discovery orbital arc is then extended by 10- to 20-years. Although not of primary interest to Planetary science, LONEOS images can also be searched for other transient astronomical phenomena. A small amount of data analysis and interpretation will be performed to validate the image products.

PDS Interactions

Following discussions with Planetary Data System - Small Bodies Node (PDS-SBN) personnel, we have created a plan for archiving this image data in FITS format, together with explanatory documentation, and ancillary PDS files in the PDS-SBN, the repository of other NEO survey image datasets (e.g., Bauer, J.M. and Lawrence, K.J., Eds., Near

Earth Asteroid Tracking V1.0. EAR-A-I1063-3-NEATV1.0. NASA Planetary Data System, 2013).

Cristina Thomas/Northern Arizona University
The MIT-Hawaii Near Earth Object Spectroscopic Survey

The MIT-Hawaii Near-Earth Object Survey (MITHNEOS) has systematically obtained near-infared spectra of near-Earth Objects (NEOs) using SpeX on the NASA IRTF (Rayner et al. 2003) since 2000. Over the years the program has obtained spectra of nearly 1000 NEOs. Within this sample, we have observed > 350 Potentially Hazardous Asteroids and approximately 450 objects with delta-V < 7 km/sec. All spectra from this survey are made available for the community shortly after observation at http://smass.mit.edu/minus.html.

This program has had a substantial and continuous impact on NEO science, including: (1) the determination of NEO spectral properties for population distribution, source regions (Binzel et al. 2004, 2019); (2) an estimation of the number of hydrated bodies in the NEO population (Rivkin & DeMeo 2019); (3) an exploration of space weathering trends on carbonaceous asteroids and their links to laboratory irradiation experiments of carbonaceous chondrite meteorites (Lantz et al. 2018); (4) the determination of the accuracy of near-ir spectral slopes, a prominent distinguishing feature of asteroids from two decades of observations, enabling better interpretation of featureless spectra (Marsset et al. 2020); (5) an enhanced understanding of space weathering and refreshing mechanisms (Vernazza et al. 2009, Binzel et al. 2010, DeMeo et al. 2014); (6) the identification of links between meteorites and the main belt source regions of NEOs (Vernazza et al. 2008, Thomas & Binzel 2010); (7) the characterization of extremely small and rapidly rotating NEOs (Polishook et al., 2012); (8) the development of techniques to determine albedo and spin orientation from thermal emission past 2 microns (Rivkin et al. 2005, Moskovitz et al. 2017); (9) an estimation of the dormant comet contribution to the NEO population (DeMeo & Binzel 2008); and (10) the classification of spectra via a taxonomy used by the community (DeMeo et al. 2009).

The primary goal of the proposed work is to spectrally characterize newly discovered NEOs and PHAs. Using data from the IRTF we will:
1. Will use the NASA IRTF's SpeX instrument to obtain > 220 new prism (0.7-2.5-microns) and >15 LXD short (1.7-4.2-microns) observations of high priority near-Earth objects.
2. Improve our understanding of the compositional distribution of the near-Earth asteroid population with a focus on its dependence on asteroid size.
4. Examine the distribution of volatiles in the near-Earth asteroid population via an analysis of 3-μm spectral features.
3. Rapidly release all obtained spectra and observing information to the community to maximize the science impact and utility of these data.

Targets will be selected from NEOs observable from the NASA IRTF on the allocated dates. Priority will be given to newly discovered NEOs, PHAs, and low delta-v targets. This survey typically receives approximately 1 night per month of observing time. Taxonomic classification will be done within the Bus-DeMeo classification system. Scientific analysis will use established techniques and tools where appropriate, such as principal component analysis, band parameter analysis, modeling of thermal tails, Minimum Orbit Intersection Distance (MOID) calculations, and comparison with the RELAB meteorite database.

The proposed work is relevant to the Yearly Opportunities for Research in Planetary Defense program because we will perform new ground-based astronomical observations of NEOs. A subset of our targets will be newly discovered targets which will enable rapid characterization of those objects.

Quanzhi Ye/University of Maryland
Tracking and characterization of NEOs with extremely low perihelia

We propose to conduct a targeted investigation of the Near-Earth Objects (NEO) discovered and only observed by heliophysics assets, primarily the Solar and Heliospheric Observatory (SOHO) spacecraft. SOHO is a heliophysics mission operated at Sun-Earth L1 point that is able to continuously monitor the near-Sun sky, and hence is able to find objects that are extremely difficult to detect from the ground. SOHO has discovered at least eight NEOs, all of which have small perihelion distances of <0.1 au. Though bearing cometary designations, the nature of these objects is not clear. They also tend to have poorly constrained orbits due to the large angular size of SOHO s pixels, short orbital arcs, and the difficulty to follow up and track these objects from the ground. Though only a tiny fraction of the NEO population, these objects pose a considerable threat to the Earth itself as well as human and robotic explorers beyond the Earth due to their uncertain orbit and their ability to eject streams of debris into interplanetary space.

The specific goals of our project are: (1) reduce the orbital uncertainty of these objects by conducting a thorough search for detections in public and proprietary archives, as well as carrying out new targeted recovery campaigns; (2) perform numerical simulations to understand the dynamical history of these objects, as well as the formation and evolution of the debris streams that they may produce; and (3) perform a completeness test on the data collected by the heliophysics assets to constrain the population of these objects. The ultimate goal is to understand the physical and orbital properties of these objects and to investigate the likelihood of future encounters with the Earth.

Our proposed work is within the scope of the YORPD element, as it seeks to understand the orbital distribution, behavior, evolution, and impact to the Earth of NEOs with extremely low perihelia, a small but poorly understood subset of the NEO population.

Our project is directly relevant to the NEO Science objective of the YORPD program, as it will conduct new observations and perform analysis on archival data to enhance our overall understanding of the NEO population. Our project has a deep connection to NEO science making YORPD the most appropriate element for the work proposed.

Juno Participating Scientist Program
Abstracts of selected proposals
NNH21ZDA001N-JPSP

Below are the abstracts of proposals selected for funding for the Juno Participating Scientist Program. Principal Investigator (PI) name, institution, and proposal title are also included. 27 proposals were received in response to this opportunity. On November 12, 2021, 10 proposals were selected for funding.

Ermakov Anton/ University of California, Berkeley
Jupiter's dynamic tides non-perturbatively
Juno's Extended Mission measurement of Jupiter's dynamic tides will provide non-degenerate information about the interior of Jupiter as compared to the static gravity field. The dynamic tidal response is uniquely sensitive to the compositional gradients sustained by stable stratification. The proposed investigation will enhance the scientific return of Juno as it will enable fully exploiting the accuracy of Juno's tidal Love number measurements.
Vorontsov et al. (1984) used normal mode expansion of tidal flow and showed that tidal Love numbers of Jupiter can be dynamically amplified compared to the equilibrium tidal response. However, the Juno data (Durante et al., 2020) showed that Jupiter's k22 tidal Love number is 4% lower than the equilibrium Love number predicted by Wahl et al. (2017) using the internal structure model optimized to reproduce the observed static gravity field. Idini & Stevenson (2021) and Lai (2021) showed that, in addition to potential dynamic amplification of tidal response, the Coriolis force acting on the tidal flow could explain the lower observed value of the tidal Love number k22. However, there were several simplifications in these works. First, the planet was assumed spherical, thus neglecting the effect of the oblateness of normal modes and Love numbers. Second, a polytropic equation of state was used to model Jupiter's interior. Thus, the current constraints on Jupiters interior from the Juno observations were not exploited. Third, the differential rotation of Jupiter (e.g., Kaspi et al., 2017) was not taken into account in computing the coupling of normal modes by the Coriolis force. These three simplifications will be retired in our proposed investigation, thus bringing the dynamic tidal response analysis from the proof of concept level to the level of a science tool.
We propose, for the first time, to compute the dynamic Love numbers of Jupiter with a non-perturbative approach. Our proposed modeling consists of three steps. First, the equilibrium internal structure is computed using the non-perturbative Concentric Maclaurin Spheroids method rotation (Hubbard 2013; Militzer et al., 2019). Second, a Rayleigh-Ritz with Continuous Galerkin finite element-based approach is used to compute the normal modes of a planet in the presence of an essential spectrum. Eigenvalues and eigenfunctions are then found as a solution to the quadratic eigenvalue problem (Jia et al., 2019). Third, the tidal flow is expanded in terms of the derived eigenfunctions in a manner similar to Lai et al. (2021), which yields dynamic tidal Love numbers.

Differential rotation enters the tidal Love number computation in two ways. First, it affects the shape of the equipotential surfaces and thus affects the geometry of the internal structure. Second, it affects the Coriolis force and, thus, Coriolis coupling between normal modes.

The comparison between the observed values of Love numbers and our modeling would shed light on the compositional gradients within Jupiter. Compositional gradients can lead to internal regions that can support the propagation of internal gravity waves, which would be naturally found as g-modes in our finite elements calculation. Wahl et al. (2017) predict two such non-neutrally buoyant layers within Jupiter. First, a deeper layer with a compositional gradient arising from the dilute core. Secord, a shallower helium rain layer, in which the helium abundance steadily grows with depth. Our proposed investigation would bring together the non-perturbative internal structure modeling along with non-perturbative tidal response analysis, thus enabling to constrain the radial extent and compositional change within stably-stratified regions, which is critical for understanding the origin and evolution of Jupiter. Finally, the developed methodology would be readily applicable to studying the dynamic tidal response of other rapidly rotating gas giants in the Solar System and beyond.

Goossens Sander/ NASA Goddard Space Flight Center
Galilean Satellite and Jupiter Gravity Science with Juno Extended Mission Data
I propose to use radio science data from Juno's Gravity Science instrument, together with camera data from JunoCam, to determine gravity field models and related geophysical parameters for the Galilean satellites Ganymede, Europa, and Io, and for Jupiter. Studies concerning the moons using radio science data are listed as particularly desired in the solicitation. My proposed analysis will be independent from the existing gravity science team, and I will apply unique tools and analysis methods that will broaden and complement their efforts. This will result in robust models of the gravity fields of the moons and Jupiter, and of the tidal response of Io and Jupiter. These results will constrain models of the interior and evolution of the moons and Jupiter, and will thus have an impact on solar system studies.
In addition to the standard analysis of Doppler tracking data to determine gravity field models, I will apply unique approaches that are designed to improve the estimates of the gravity and tidal parameters, and address specific issues with data coverage and force modeling.
During the flybys of the Galilean satellites, the spacecraft can experience perturbations from the gravity field at scales smaller than those captured by the estimated models. This can lead to the occurrence of leakage, where the full resolution of the gravity field cannot be accounted for. I have developed and implemented a method to account for these leakage effects. This method can minimize the bias that otherwise would affect the solution, and that would greatly affect the interpretations based on the gravity model.
I have also developed a method to localize Doppler data by means of line-of-sight (LOS) accelerations. These accelerations are more sensitive to small scale features when compared to Doppler data. The LOS accelerations can be used, in combination with different representations such as mass concentrations (mascons), to determine local variations in the gravity field. This will be especially impactful for Ganymede, for which mascons have been inferred from Galileo data. In addition, the ground tracks of the Io flybys indicate that they may come close to volcanoes or tall mountains. Using the LOS accelerations may allow for probing the gravity signal of such features.
Two flybys are focused on the moon Io to determine the time-varying tidal signal raised in its gravity field by Jupiter. This will put constraints on the likely presence or state of a magma ocean in its interior. Most analysis of radio science data implicitly assumes an equilibrium tidal response, that is, as if the whole body was an elastic solid. Yet, more than 100 years of ocean

tidal dynamics research for Earth clearly shows that a fluid dynamic response must be considered. I will apply models of the fluid tidal response in addition to the standard analysis, which will allow for possible constraints on the state of the ocean.
Initial analysis indicates that images from JunoCam will have overlap on Io's surface, at sufficient resolution. Shared features in overlapping images can be used in a novel data type called image constraints that uses images from the different flybys to create a differenced measurement. Such a differential measurement is very powerful to determine parameters that induce time-varying signals, and this will thus improve the determination of the Love number.
This proposal is relevant to the Juno Extended Mission Participating Scientist Program. I have extensive expertise in the analysis of radio science data. I will focus on the studies of the Galilean satellites, and I will contribute to studies of Jupiter's interior structure models, by providing independent gravity field models estimated with different techniques, for all targets. This will enhance Juno's science return by providing critical data analysis and results for top science priorities of the Juno mission.

Vogt Marissa/ Boston University
Structure and Dynamics of Jupiter's Duskside Magnetosphere
Science goals and objectives
Jupiter's magnetosphere displays strong dawn-dusk asymmetries in quantities such as the plasma velocity, magnetic field structure, and plasma sheet thickness. Ultimately these local time asymmetries arise because of the nature of the solar wind flowing past an obstacle, in this case Jupiter's rapidly-rotating magnetosphere, but many of the physical processes that produce these local time asymmetries, and their consequences for the aurora, are relatively poorly understood. Juno's extended mission orbit will offer an unprecedented opportunity to study the structure and dynamics of Jupiter's duskside magnetosphere. Our proposed work will address the following questions: what are the properties of Jupiter's duskside lobe field? What is the structure and variability of the magnetic field bendback in Jupiter's duskside magnetosphere and how does it influence the aurora? Why is Jupiter's plasma sheet thickest near dusk?
Methodology
Our work will involve analysis of Juno MAG, JEDI, JADE, Waves, and UVS data. We will analyze periodic fluctuations in the radial and azimuthal components of the magnetic field data to identify trends in how the plasma sheet and lobe properties vary with radial distance and local time. We will also use the magnetic field data to examine the latitudinal dependence of the magnetic field direction away from corotation (i.e. its "leading" or "lagging" configuration) and calculate the resulting field-aligned currents and their variability. Finally, we will examine the plasma energy and pitch angle distribution measured by JADE and JEDI in Jupiter's noon-dusk region to determine how plasma is energized. We will compare data to model predictions that suggest that nonadiabatic heating produces a pressure anisotropy that leads to the plasma sheet thickening near dusk.
This work is relevant to the Juno Participating Scientist program because it will use new Juno data to study the structure of Jupiter's magnetosphere. Our work will characterize magnetospheric local time asymmetries and the general structure and dynamics of the duskside magnetosphere. We will predict the solar wind conditions upstream of Jupiter during the Juno EM, which will provide important context for the Juno data and analysis that addresses EM science goals "M2. Explore the region near Jupiter's polar magnetopause to investigate the

interconnection and accessibility to the interplanetary medium" and "S1. Investigate satellite interactions with the Jovian magnetosphere and characterize Ganymede's magnetosphere".

Lian Yuan/ Aeolis Research, Inc.

Interpreting Juno MWR Observations Using Global Modeling of Water and Ammonia Cycles Across Scales on Jupiter

Recently, Juno MWR measured deep water and ammonia vapor distributions on Jupiter for the first time. The most distinctive feature is that ammonia far below Jupiter's ammonia cloud base, from 2 bars to about 60 bars and at most latitudes up to 40 degree in both hemispheres, is depleted by 2-3 times compared to the deep ammonia abundance, while it has slightly higher concentrations immediately below the ammonia cloud in a layer between 0.7 and 2 bars (likely a result of re-evaporation of precipitation) and becomes abundant in the regions deeper than 60 bars (a result of deep mixing). The exception is the equatorial band, which has a much higher ammonia abundance compared to other latitudes between 0.7 bars and 40 bars. Water vapor abundance was also retrieved at a very narrow latitudinal region (0 - 4 degree north) from the MWR measurements of brightness temperature in pressure range between 0.7 and 30 bars. Outside of this equatorial band, the brightness temperature measured by the MWR exhibited great variability with latitudes (though temporally stable), which made it difficult to retrieve the water abundance at higher latitudes. It remains unclear whether the retrieved water vapor abundance is representative of the global water abundance.

The formation of the ammonia-poor layer is puzzling because ammonia below the water cloud base was expected to be well mixed by dry convection driven by the internal heat flux. This expectation comes from the assumption that Jupiter's interior is highly convective; indeed, Galileo probe measurements revealed an atmosphere that was close to a dry adiabat from 1-22 bars, suggesting a well-mixed atmosphere over this depth range. Additionally, ammonia appears to be more abundant in the belts than in the zones in the region between 40 and 60 bars, implying upwelling of ammonia-rich air from below in the belts. This behavior is opposite to the Voyager observations of upwelling in the zones and downwelling in the belts.

We propose to apply a new, multi-scale Jupiter atmospheric model (JupiterMPAS) to investigate the key mechanisms including mesoscale downdrafts, Mushball microphysics and Ekman layer effect and evaluate their relative importance in the weather layer and the region below the water cloud base. We expect to achieve three objectives: 1. understand whether mesoscale downdrafts can explain the observed ammonia depletion; 2. understand whether Mushball microphysics can explain the observed ammonia depletion; 3. explore implications of ammonia distribution for dynamic structures below the water cloud base. The proposed studies provide an opportunity to better understanding the fundamental processes that shape the thermal structures and tracer distributions in the regions closely related to the weather layer. Better understanding and modeling of the mechanisms behind the ammonia distribution will also directly help to disentangle the contributions of atmospheric temperature, ammonia vapor, and water vapor to the brightness temperature measured by the MWR globally, therefore providing an opportunity to retrieve water vapor abundance away from the equator.

The proposed work is directly relevant to the Juno Extended Mission Science objectives "Atmosphere studies: Investigate Jupiter's northern latitudes, gather information on its water/ammonia abundance, polar cyclones, ... and variability of lightning", as well as the investigation desired by Juno Extended Mission "Physics of lightning in Jupiter's atmosphere, atmospheric dynamics, hazes, vertical stratification of clouds"

Keane James/ Jet Propulsion Laboratory
The Juno Gravity ⇄ Geology Pipeline

Long-wavelength gravity provides key constraints on the interior structure and geologic processes of planetary bodies. In particular, spherical harmonic degree/order-2 gravity is related to both the radial density structure, and how the body deforms in response to rotation and tides. Most studies assume that these two effects (radial density structure and tidal/rotational deformation) dominate long-wavelength gravity, and this assumption underlies the current state of knowledge of Io, Europa, and Ganymede. However, every time we investigate planetary gravity fields in more detail, we consistently find that long-wavelength gravity is more complicated. Geologic processes—including impacts, volcanism, volatile loading, tectonics, etc.—all contribute to long-wavelength gravity. Understanding this "geologic contamination" will be critical to Juno's Extended Mission and its investigation of the Galilean satellites.

I propose a comprehensive, multi-pronged investigation of the long-wavelength gravity fields of the Galilean satellites, and how they are affected by geologic processes. I call this the GRAVITY⇄GEOLOGY PIPELINE. There are two key components:

[1] GRAVITY→GEOLOGY: I will use Juno gravity data to invert for the contribution of geologic phenomena to the long-wavelength gravity fields of the Galilean satellites. I will utilize both gravity science data (line-of-site gravity) and data products derived by the Juno team (spherical harmonic models of the gravity field), coupled with models of known and predicted geologic phenomena to determine their contribution to the long-wavelength gravity fields of these bodies.

[2] GEOLOGY→GRAVITY: I will use published global datasets, including geologic maps and topographic data, to forward model how different geologic phenomena may contribute to the long-wavelength gravity fields of the Galilean satellites.

In the end, I will provide constraints on the gravity signature of different geologic phenomena and how those features contaminate long-wavelength gravity. These measurements are critical to determine the interior structure of the Galilean satellites, and enable a variety of spin-off investigations. In particular, I propose to use these results for a detailed investigation of reorientation of the Galilean satellites, including testing long-standing questions about true polar wander and non-synchronous rotation.

In addition to the GRAVITY⇄GEOLOGY PIPELINE, I also propose a SCIENCE VISUALIZATION AND SYNTHESIS task, which is uniquely designed to leverage my unique expertise in science illustration to enhance science outcomes and facilitate collaboration and development of new ideas across the Juno team.
This proposal is directly relevant to the Juno Participating Scientist Program call, as it is responsive to the desired investigation, "studies of Galilean satellites Ganymede, Europa, and Io, e.g., analysis of radio science […] data", and two of the Extended Mission science objectives:

“Europa: Investigate the ice shell […]” and “Io: Constrain the global magma ocean […]”. The proposed research utilize data from Juno’s gravity science experiment, although there are substantial synergies with other remote sensing datasets—including the induction experiment (MAG) and visible/infrared imaging of the surfaces (JIRAM, JunoCam). This sort of integrated study is only feasible from within the Juno team. I have a demonstrated history of such collaborations (GRAIL, New Horizons), and my unique expertise in long-wavelength gravity and topography of planetary bodies makes me uniquely qualified for the proposed work effort. My methodology is resilient to the specific flyby geometry and data quality (and could be used to inform mission planning). The outcome of this proposal may also inform the forthcoming Europa Clipper and JUICE missions.

Louis Corentin/ NASA Foreign PI Support Organization
Study of Jupiter's auroral emission at multi wavelengths
The magnetosphere of Jupiter produces a wide variety of auroral emissions, covering the electromagnetic spectrum from X-rays, through Ultraviolet (UV) to radio waves (up to decametric wavelengths). These emissions reveal the complex interactions between ions, electrons, and magnetic fields, and show the great variety of acceleration processes at work in the Jovian polar regions. These regions are the site of intense wave-particle interactions, producing the auroral emission in the X-rays, UV and radio wavelengths. Combination of in situ fields and particles investigation along with remote sensing is essential to uncover the underlying physics of this dynamic region.
NASA's Juno mission is revolutionising our understanding of the jovian system, its magnetosphere, moons, and atmosphere. With the approved extension of the Juno mission to 2025 and the associated evolution of the orbit, there is an opportunity for the spacecraft to explore new regions of Jupiter's magnetosphere and to continue to enable discovery-mode science. At the same time, there is an ever-growing archive of ground-based and space-based observations of Jupiter in multiple wavelenghts from radio to Ultraviolet (UV) to X-ray. We propose an holistic programme of data analysis and modelling to unveil the physics of the coupled solar wind-magnetosphere-ionosphere system, with specific focus on the auroral emissions and their link to magnetospheric dynamics.
Our proposal is organized around three main scientific questions. The first one aims at understanding the mechanisms that drive multi wavelength auroral emission (radio, X-rays, UV) in the polar regions. The second one will focus on the interaction between the solar wind and Jupiter's emissions (X-rays and radio), during compression of the magnetosphere due to the arrival of strong solar wind. The third one will investigate the interaction between Jupiter and its Galilean moons and the induced radio emission produced by those interactions.
To address the scientific questions, this proposal draws on the unique expertise and leadership of the team members with complementary datasets. Our methodology will rely on a combination of Jupiter orbital measurements from Juno, Earth-orbiting telescope measurements (Chandra X-ray telescope), ground-based radio sensing (I-LOFAR, NDA, NenuFAR), and advanced simulations of radio emission (ExPRES code). This methodology builds on our proposing team's unique mix of proprietary data access, membership of scientific teams, data analysis and simulation expertise.

Nordheim Tom Andre/ Jet Propulsion Laboratory
Europa and Ganymede: Disentangling exogenic vs endogenic controls on surface composition

This project will investigate the surfaces of Europa and Ganymede, comparing the effect of charged particle weathering versus endogenic ocean world processes. To accomplish this, I will make use of observations by the Jovian Infrared Auroral Mapper (JIRAM), the Jovian Auroral Distributions Experiment (JADE), and the Jupiter Energetic Particle Detector Instrument (JEDI), as well as computer modelling of charged particle interactions with surface material on the moons. This combined approach of remote sensing and in-situ charged particle analysis, along with the data gathered by Juno during the extended mission, will provide an ideal opportunity to understand the processes that have shaped the surfaces of Europa and Ganymede.

Objectives:

1. Determine the nature and spatial distribution of non-water ice surface constituents as possible tracers of geologic activity and ocean chemistry
2. Quantify the energy input from Jupiter's magnetosphere and evaluate the effect of endogenic versus exogenic controls on surface composition.

Tasks:

1. Analyze near-infrared spectra of Europa and Ganymede gathered by JIRAM as part of the Juno extended mission. Identify and determine the distribution of non-water ice spectral features.
2. Carry out modelling of charged particle surface modification using measurements by JADE and JEDI near the moons as an input to existing computer models.
3. Compare the presence and spatial distribution of non-water ice surface constituents with predictions from computer modelling.

Expected Significance:

My involvement as a participating scientist will enhance the scientific return of the Juno Extended mission by complementing the existing Juno objectives and team expertise. Specifically, I will contribute my unique combination of expertise in remote sensing of icy objects and satellite-magnetosphere interactions, as well as leveraging already existing tools and analysis workflows that I have developed. The proposed work will significantly improve our understanding of satellite-magnetospheric interactions and sputtering which are called out as high priority topics in the Juno PSP solicitation.

Phipps Phillip/ University of Maryland Baltimore County
Io Plasma Torus Radio Occultations

This proposal aims to use radio occultations to measure the plasma properties of the Io plasma torus. These measurements, which include scale height and total electron content, give insight into magnetospheric plasma at distances between 5 and 8 Jupiter radii from Jupiter. This is the region around Jupiter’s moon Io which is the largest source of the plasma in Jupiter’s magnetosphere. Thus, this proposal will address the Juno science objective: “Investigate the spatial and temporal variability of the Io and Europa plasma tori to address the transport of mass and energy through Jupiter’s inner magnetosphere”. Radio occultations will map the vertical structure of the torus perpendicular to the plane of rotation. During Juno’s prime mission the spacecraft made measurements well outside the regions probed by Juno radio occultations making it difficult to make comparisons to in-situ measurements. During most of the Juno extended mission the spacecraft will pass through regions just outside the region probed by radio occultations. Thus, combining radio occultations with in-situ measurements by the Juno plasma instruments, JADE , can complete the picture of the plasma distribution between the moons Io, Europa, and Ganymede. The real time calibration between radio occultations and in-situ measurements will help to better understand the plasma variability. These studies will be enabled by the collaboration between radio occultations and instrument teams. Radio occultations will not impact the current plan of operations as they require the dual band frequency tracking already required by the Gravity science measurements during Juno Perijove. The radio occultation technique was demonstrated by measurements performed during the Juno prime mission. The proposed work will build on the previous experience of the proposer in working with Juno radio science data during the Juno prime mission.

Siegler Matthew/ Planetary Science Institute

Microwave Measurements of the Galilean Satellites

In this proposed work we will interpret the Microwave Radiometer (MWR) data of the Juno flybys of Ganymede, Europa, and Io. Microwave radiometry is widely used for atmospheric temperature, density and composition of atmospheres, such as Juno's MWR was designed to do. However, such data are also profoundly important in understanding solid surface temperatures and structure. Solid surfaces can be thought of as a very dense atmosphere, with MWR soundings reaching 10's of meters into the interiors of Europa and the other Galilean satellites, rather than the 100's of kms in Jupiter's atmosphere.

Specifically, microwave brightness temperatures are controlled by:

1) the wavelength of the observation (with longer wavelengths seeing deeper), 2) the physical temperature of the subsurface (which depends on illumination, thermal properties and geothermal heat), and 3) the dielectric properties of the subsurface (which depend on material properties such as density and minerology of the material).

In a series of NASA-funded studies, the PI has used data from the Earth's Moon from the Chang-E orbiters (which carried a 3-37 GHz radiometer, similar to MWR) and observations at ~1.4 GHz and 420 MHz from the VLA to reveal the subsurface temperature, dielectric, and density structure of much of the lunar surface. One of the most intriguing outcomes of this research has been the proof-of-concept of using microwave radiometry to back out the subsurface thermal gradient and therefore geothermal heat flux of the Moon. This has led to a NASA DALI-funded microwave spectrometer instrument based on the Juno MWR instrument specifically designed to constrain the geothermal gradient and heat flux of the Moon or other bodies without requiring drilling.

Here we describe our strategy to used radiative transfer models of the MWR data of the Galilean satellites to constrain information about their the near surface structure, composition, and temperatures. Short wavelength data (1.37, 3, 5.75 cm) is dominated by near-surface density, dielectric properties, and diurnal temperatures. These data will allow the PI to constrain the surface density on Ganymede and Europa (which is important for potential landing site conditions) and potentially detect anomalous dielectric materials on the surface of Io. Long-wavelength (11.55, 25 and 50 cm) data will likely see well below the diurnally varying surface, and allow for constraint of the geothermal gradient, which is especially interesting on ocean worlds such as Ganymede and Europa, where the geothermal gradient would provide a strong constraint on the thickness and rheology of the ice shell. We will model shell thickness and both near and deep subsurface temperatures using JunoCam albedo.

We understand data will be limited. The 1000 km Ganymede flyby will result in ~200-350 km surface resolution depending on frequency (or about 15-25 data points across the body at each frequency); the 320 km flyby of Europa about 67-112 km resolution (27-46 data points); the 1500 km Io flyby will result in only 315-530 km data (7-12 data points). However, these are also limited by the speed of the flyby as MRW is fixed to the rotating spacecraft, resulting in gaps between this full coverage. Assuming a 5 rotation per minute rate we expect Ganymede data will be limited to about 24 points per frequency, Europa only about 6-7 points at each frequency, and Io as few as 2 resolved points. However limited, we argue the uniqueness of this data provides a compelling case for detailed analysis.

This proposed work directly addresses the objectives of the Juno Participating Scientist Program as it uses MWR data (aided by JunoCam) to look at the Extended Mission flybys of the Galilean satellites by Juno. This work will also feed-forward into currently funded NASA efforts, such as the Europa Clipper mission, potential Europa surface lander, potential missions to Io, and our DALI microwave radiometer.

Withers Paul/ Boston University

Jupiter's ionosphere: Magnetic effects on plasma densities

Jupiter's ionosphere: Magnetic effects on plasma densities

This proposed investigation will measure profiles of Jupiter's ionospheric electron density with radio occultations, archive these profiles on the Planetary Data System, and use these profiles to characterize how densities in Jupiter's ionosphere depend on magnetic location.

Magnetosphere-ionosphere coupling is extremely strong at Jupiter, playing a major role in determining conditions in the ionosphere and neutral upper atmosphere. This is most visibly manifested in magnificant auroral emissions seen near the poles, where magnetospheric particles precipitate into the atmosphere/ionosphere. This energy input heats the upper atmosphere/ionosphere, ionizes neutral atmospheric species, modifies chemical composition, and drives dynamical and electrodynamical motions. These considerations motivate Goal 1, which is "Determine how magnetosphere-ionosphere coupling affects Jupiter".

Progress towards Goal 1 will be delivered by achieving Objective 1, which is "Characterize how electron densities in Jupiter’s ionosphere depend on magnetic location". Several lines of evidence show that Jupiter's ionosphere is strongly affected by magnetic location, including infrared remote sensing observations of H3+, Juno/JADE observations of low energy ions, and unpublished Galileo radio occultation profiles. Yet existing observations are insufficient to adequately characterize these effects. Juno Extended Mission observations are essential for achieving Objective 1.

We will produce tens of ionospheric electron density profiles by analysis of routine Juno Gravity Science observations during Jupiter occultations that occur near perijove. Existing tools that we have demonstrated on equivalent Cassini data at Saturn will be used. Observations will sample multiple locations within auroral regions, thereby characterizing how ionospheric conditions vary with the flux of precipitating magnetospheric particles and related factors.

Plans have been developed to mitigate several unique challenges presented by Juno at Jupiter: Jupiter's oblateness, the descent of Juno to ionospheric altitudes during occultations, and multipath effects. The tools we have exercised successfully at Saturn will address oblateness and Juno's low altitude. Multipath effects, which degraded the quality of earlier radio occultation observations at Jupiter, will be mitigated by using Juno Ka-band radio signals, which are much less susceptible to this undesirable propagation phenomenon than the lower frequency S-band radio signals used by Galileo and other early missions.

This proposed investigation is aligned with Juno extended mission science objective A4: Investigate Jupiter’s upper atmosphere, ionosphere and auroral heating and energy transfer to lower latitudes via radio occultations.

EnVision VenSAR Science Team
Abstracts of selected proposals
(NNH21ZDA001N- VENSAR)

Below are the abstracts of proposals selected for funding for the VENSAR program. Principal Investigator (PI) name, institution, and proposal title are also included. 41 proposals were received in response to this opportunity. On June 9, 2022, 14 proposals were selected for funding.

Paul Byrne/Washington University
EnVisioning Venus: Using VenSAR to Understand the Past and Present of the Second Planet

I propose to join the VenSAR Science Team (VeST) as an expert in the use of radar data to understand present and past volcanic and tectonic processes and properties on Venus.

As a member of the VeST, I will assist in:
a) Refining the VenSAR instrument's scientific objectives and requirements to achieve the EnVision mission objectives;
b) Identifying target areas on Venus for VenSAR observations;
c) Defining the scientific data products required to achieve VenSAR objectives;
d) Providing expert guidance on the impacts of engineering decisions and design trades for the VenSAR instrument to EnVision mission science; and
e) Ensuring that all synergistic and multidisciplinary science to be enabled by combining VenSAR with EnVision's other instruments, and with data returned by other Venus missions, is considered in the development of the VenSAR instrument.

My relevant scientific expertise includes studying the nature, composition, and deformational history of tesserae units on Venus, identifying a previously unrecognized form of tectonic deformation throughout the planet's lowlands driven by mantle motion, and testing the hypothesis that at least some tesserae on Venus were formed geologically recently by the deformation of plains materials. I was also the Chair of the Venus Panel of the 2023 2032 Planetary Science and Astrobiology Decadal Survey, and I am a member of the Venus Exploration Analysis Group (VEXAG) Steering Committee.

Together, these experiences strongly enable me to understand Venus science at the systems level, allowing me to ensure that the science campaign for the VenSAR instrument is as optimized as possible with the other EnVision instruments, with the VERITAS and DAVINCI missions, and with the scientific cross-cutting questions of the 2023 2032 Decadal Survey and the VEXAG Goals, Objectives, and Investigations document. Moreover, in July 2022 I will become the Manager of the PDS Geosciences Node and will thus be uniquely positioned to provide advice to the VeST and the EnVision team generally regarding data archiving plans, standards, and timelines.

This proposal also includes a request to join the EnVision Science Study Team as a VeST member.

Lynn Carter/University of Arizona
EnVision VenSAR Science Team Participation: Polarimetry and Interdisciplinary Science

The VenSAR instrument on the ESA EnVision mission was designed to address many key science objectives at Venus through the use of high-resolution synthetic aperture radar (SAR) polarimetry, polarimetric radiometry, SAR stereo topography and altimetry. The current sediment budget (sources and sinks) on Venus is very unknown, and the EnVision mission offers a unique opportunity to better map the surface and near-subsurface structure in regions of interest. The VenSAR polarimetric radar images are well suited to addressing long-standing questions about the amount and nature of Venus surface sediments.

As a VenSAR team member, Dr. Carter proposes to develop the polarimetry processing algorithms and produce the science data products related to polarimetry. In particular, she will take a leadership role in developing SAR imaging polarimetry requirements, calibration, processing, PDS archiving, and community engagement with understanding polarimetry products. Dr. Carter will additionally work with the VenSAR and Subsurface Radar Sounder teams to develop products and operations plans that will enable joint science investigations. Dr. Carter will also lead the development of a set of targets for polarimetry data acquisition.

Dr. Carter was a named participant in the EnVision proposal and has prior experience with radar mission teams and with radar instrument development. She is a team member on the SHARAD sounding radar on Mars Reconnaissance Orbiter and the RIMFAX ground penetrating radar on Mars2020/Perseverance. She has also been a team member and Deputy PI of the Mini-RF instrument on Lunar Reconnaissance Orbiter, which is a polarimetric SAR. She has led multiple grants to develop a P-band (70 cm wavelength) polarimetric SAR with NASA Goddard (SESAR), and has experience with issues relating to polarimetry calibration and data product generation. Dr. Carter also proposes to be the VenSAR Team Lead.

Dr. Carter's work will contribute to several activities expected for members of the VenSAR science team, including refining instrument objectives, targeting, data product definition, synergistic activities between VenSAR and other instruments, and VenSAR development, engineering trades, calibration, and documentation. Dr. Carter's proposed tasks will contribute to detailed development of the following Observation Requirements in the EnVision Science Traceability Matrix (Yellow Book): OR-1.1 regional surface mapping, OR-1.2 targeted surface mapping, OR-3.2 surface polarimetric reflection and emission properties and OR-4 Subsurface material boundaries.

Indujaa Ganesh/University of Arizona
VenSAR radiometry observations of Venus: characterizing surface dielectric properties and potential volcanic activity

This is a proposal for participation in the VenSAR science team to contribute to the planning of VenSAR radiometry observations. Radiothermal emission from a planet's surface contains information about material dielectric properties, microwave loss properties, and shallow-subsurface thermal structure. Prior passive microwave observations of Venus's surface from Pioneer and Magellan orbiters have been valuable in studying spatial trends in surface microwave emission, especially as a function of elevation. These observations, however, were restricted to single polarization and single acquisition geometry for any given location on the surface. EnVision's VenSAR instrument will acquire passive emission measurements at two orthogonal polarizations (H and V) and multiple viewing geometries for the first time, making for a more valuable opportunity to characterize Venus's surface material properties. Additionally, thrice-repeated passive observations of the surface will be valuable in monitoring any high surface emission associated with potentially recent volcanic activity. We propose two primary tasks, grounded in prior observations and theoretical knowledge of Venus's surface, that will aid in VenSAR radiometry observation planning (stand-alone and synergistic) and maximizing the usefulness of the observations.

Task1. We will Magellan observations to identify targets on the surface that are smooth at VenSAR wavelength (~9.4 cm) scales that are suitable for material dielectric characterization and absolute radiometry calibration.

Task 2. We will explore opportunities for synergistic observations between VenSAR and VenSpec-M to maximize detection of any recent volcanic activity by simulating the surface emission these instruments would measure, at corresponding wavelengths, from lava flows that are a few hours to three months old.

In addition to these proposed tasks, the PI will participate in additional science team activities including general targeting and operations, additional instrument calibration efforts, attending team meetings, contributing to discussions, and building open-source, community tools that enhance data products accessibility and usability.

The proposed activities address the objectives of the VenSAR Science Team (VeST) participation program. The primary tasks are directly relevant to science objectives 2.2.3 (surface modification) and 2.2.5 (present volcanic activity) listed in the EnVision Yellow Book; the tasks are also relevant to science objectives 2.2.1, 2.2.2, and 2.2.7.

Robert Herrick/University of Alaska, Fairbanks
Application for membership to the EnVision VenSAR Science Team

As a long-time advocate for a new Venus synthetic aperture radar mission to Venus and a Core Team Member on the EnVision proposal submission, Robert Herrick is excited to have the opportunity to apply to the VenSAR Science Team (VeST). Dr. Herrick has extensive experience and qualifications relevant to VeST membership. For over thirty years he has conducted multi-disciplinary Venus research, including heavy use of SAR data from the Magellan mission. His work has made major advances in our understanding of Venus resurfacing history and global geodynamics, central science themes in the EnVision science objectives and investigations. This Venus science background will enable contributions to refining VenSAR and EnVision scientific objectives and science requirements. The wide array of topics and global scope of his research will be useful in target selection for VenSAR observations. A background in digital data processing, including delivery to the Planetary Data System of a widely used data set of stereo-derived topography from Magellan data, will inform his input into VenSAR planning for data processing and production of data products. Involvement with numerous Venus mission proposals, mission concept studies, and Venus Exploration Analysis Group (VEXAG) activities, sometimes in leadership positions, will provide a knowledge base to contribute to VeST mission design and planning activities. Included early in upcoming mission planning activities should be a reassessment of VenSAR design and data acquisition in light of the recent NASA selection of the VERITAS and DAVINCI missions, whose results will be relevant to EnVision. With Dr. Herrick's contributions to VeST activities over the next five years, VenSAR and EnVision will have an instrument and mission design and implementation plan that will result in maximum science return for this groundbreaking mission.

Kandis Lea Jessup/Southwest Research Institute
EnVision Synergies

Proposal objectives:

NASA is seeking VenSar science team members who have expertise that can guide the development and/or science targeting of the VenSar instrument in such a way that the synergistic capabilities of VenSPec, VenSAR and Venus SRS are maximized, resulting in the highest level of advancement in current understanding of Venus planetary system science.

The goal of this proposal is to demonstrate how my experience and expertise may be used to i) guide VEnSar targeting; ii) create data products that integrate VenSAR with the other instruments planned for EnVision and iii) identify studies that can validate combined VEnSar and VenSpec observations in such a way that questions of how Venus's atmosphere and climate are shaped by geological processes; and how the planet has evolved over time are explored to their greatest extent.

It is my plan to use my knowledge of the sensitivity of the cloud layer properties to variance in Venus's underlying topography to define priority surface regions that must be mapped to adequately characterize and validate the ways in which the surface morphology impacts the atmospheric behaviors, ultimately driving climate.

Furthermore, my previous experience using photochemical model to infer the expected cloud layer gas abundances based on an assumed set of conditions at the troposphere/mesosphere boundary of Venus' atmosphere can be used to develop tests that can validate/parametrize the degree to which increases in volcanically sourced gases will be detectable in the cloud layer. The combination of the photochemical modeling, 3-d general circulation modeling and the remote sensing techniques is a key multi-disciplinary skill that would be used to adequately validate complementary VEnSar and VenSpec observations.

The tools and resources for the planning of the EnVision mission priorities need to be developed and validated now to help with the completion of pre-mission publications demonstrating the potential of the EnVision mission.

Relevance to call and NASA priorities:
The VEnSAR team call specifically requests team members with expertise relevant to VenSAR, Venus science, and multidisciplinary approaches that integrate VenSAR with the other instruments planned for EnVision. My proposal will explicitly demonstrate how my membership on the team at this stage will Provide expertise and experience needed to understand and guide the synergistic, multidisciplinary potential of VenSAR observations when combined with those of the complete EnVision instrument payload identifying target regions that maximize the the synergistic capabilities of the entire EnVision payload, ultimately ensuring that entirety of the EnVision mission investigations lead to a significant advance in our understanding of the fundamental mechanics of Venus planet system, especially understanding how Venus's atmosphere and climate are shaped by geological processes.

Catherine Johnson/Planetary Science Institute
Geophysical Characterization of Surface and Near-Surface Structure on Venus with VenSAR

EnVision's unprecedented high resolution, multi-instrument suite will address key unanswered questions regarding the present-day state and history of Venus, Earth's sister planet. Critical to understanding Venus' current geological activity and long-term evolution are geophysical characterizations of the surface and shallow sub-surface structure. Here we propose two main activities to support EnVision VenSAR Science Team (VeST) efforts. First, we will identify potential target areas for VenSAR observations through further analysis of existing Magellan (MGN) data sets. Second, we will develop software and planning tools to prepare for possible InSAR opportunities to detect active lava flows from repeat-pass interferometry. PI Johnson is the proposed VeST team member, supported by junior researcher and Co-I Russell, and Collaborator Sandwell.

Activity 1 (Tasks 1 and 2): We propose two efforts related to identification of high-priority VenSAR targets. We will focus on coronae and lithospheric flexural signatures, features that are key to understanding present activity, and magmatic and tectonic history.

In Task 1, we will investigate deformation styles across moat-outer-rise signatures at coronae and other regions modeled for topographic flexure. In Task 2, we will investigate evidence for late-stage volcanism associated with corona annuli. This activity will assist the VeST team in identifying target areas for one or more of the following VenSAR observations (i) repeat 30 m observations for change detection (volcanism / mass movements), (ii) stereo SAR to estimate fault displacements and spacings, and characterize volcanic constructs and products, (iii) 10 m images to resolve details of volcanism and image regions that might be sites of recent mass movements and (iv) polarimetry to elucidate surface dielectric and roughness properties.

Activity 2 (Tasks 3 and 4): We propose to develop software and planning tools for use by the VenSAR and EnVision teams, to prepare for possible SAR interferometry (InSAR) opportunities to identify active lava flows. InSAR decorrelation is an established technique for mapping new lava flows on Earth and could provide transformative science at Venus. Unlike the InSAR phase difference approach used to detect line-of-sight ground motions, decorrelation does not require an accurate digital elevation model for correction of the topographic contribution to phase and is much less sensitive to atmospheric changes. Preliminary calculations indicate that repeat-pass InSAR decorrelation studies are possible within the EnVision orbit and science operations plans. In addition to contributing to team activities such as reports, review material and white papers, the PI can contribute, as needed / desired by the VeST team, to the evaluation of altimetry and stereo topography products. This would leverage her expertise with altimetry data sets, as well as recent mission science operations work by her group in evaluating altimetry data and digital terrain models (DTM).

Relevance: The studies proposed leverage the capabilities of VenSAR and are directed toward furthering surface and near-surface geophysical understanding of Venus. The outcomes will help address two of the three highest level EnVision science themes:

(1) How have the surface and interior of Venus evolved?
(2) How geologically active is Venus?

The proposed work contributes to several VeST proposal call activities including:

(i) identification of target areas for VenSAR observations (Activity 1),
(ii) evaluation of simulated VenSAR data (Activity 2),
(iii) defining scientific data products required to achieve VenSAR objectives (Activity 2).

Walter Kiefer/Universities Space Research Association, Columbia
EnVision VenSAR Observations of Tectonic and Volcanic Processes on Venus

I propose to serve as a member of the VenSAR science team. Under this proposal, I will work on two tasks. First, I will assess the scientific utility of the VenSAR stereo topography measurements. I will test the ability of stereo-derived topography models for Venus to be used for modeling tectonic processes by developing quantitative fault models for selected regions of the Magellan stereo DEM. I will examine faulting in three key geologic units, (1) the Maxwell Montes mountain belts, (2) the structurally complex tessera, including both the marginal belts and the plateau interior of either Ovda Regio or Tellus Regio, and (3) normal faulting and wrinkle ridges that occur in the annular trough of Artemis Corona. The modeling will be done with the elastic dislocation code COULOMB. Comparison of observed topography profiles in the study regions with a suite of numerical fault models will enable constraints on the total amount of fault offset, details of the fault geometry (fault dip and the possible presence of listric or blind faulting), and the maximum penetration depth of a given fault into the crust. Successful modeling of the Magellan stereo topography profiles would demonstrate the value of higher resolution EnVision stereo topography for modeling Venus tectonic processes. Second, in consultation with other members of the VenSAR Science Team, I will begin developing a detailed plan for targeting VenSAR observations. I specifically wish to focus on targeting of tectonic and volcanic features. This work will prioritize the key examples of various classes of tectonic and volcanic structures. This will expand upon the simplified, proof-of-concept target planning that was performed in Phase A and is necessary to ensure that EnVision will be able to observe all of the key locations that are needed to address its science requirements within the limits of available observation time and data downlink rate.

In addition, I also propose to serve as the U.S. EnVision Mission Scientist and to serve on the Phase B Science Study Team (SST). These roles build logically upon my work (2018-2021) as a NASA-appointed member of the EnVision Phase A SST. During the Phase A study, I helped to define the mission's science requirements for the Geologic History goal, the measurement requirements for VenSAR, and the required spatial coverage requirements for VenSAR observations. In addition, I served as the U.S. member of the editorial board for the Phase A study report. As a result, I already have a working knowledge of the EnVision mission design, the various instruments, the science requirements, and the current iteration of the science operations plan. I also have working relationships with most of the European members of the SST and with the ESA spacecraft engineering team. As a result, I am ready to begin immediately working productively either as the Mission Scientist or as a member of the SST, helping both NASA and ESA to maximize the overall science return from this exciting mission.
The proposed work will help to refine the VenSAR science objectives and the associated science and measurement requirements, identify priority target regions for VenSAR observations that are needed to meet these science requirements, and test the scientific utility of the VenSAR stereo topography observations as a VenSAR data product. These are directly relevant to the scope of the EnVision VenSAR Science Team program.

Scott King/Virginia Polytechnic Institute & State University
Surface Manifestations of Mantle Processes Expected for VenSAR

This proposal is for Scott King to join the VenSAR Science Team (VeST) over the period of 2022-2027. King would use geodynamic models of the Venusian surface to provide diagnostic topographic, gravity, and strain-rate maps associated with surface tectonic features on Venus, including coronae, tesserae, and proposed subduction structures.

These calculations would be the highest resolution global and regional spherical convection models ever run for Venus with lateral surface spacing of 0.3-30 km. These calculations would provide critical constraints on the VenSAR instrument requirements by testing proposed formation mechanisms and comparing the surface topography, strain-rate maps, and gravity from various formation mechanisms. Although gravity is not directly comparable with VenSAR observations, it will be used with VenSAR derived topography to constrain internal structure. To illustrate, one formation mechanism for coronae is plumelets impinging on the base of the lithosphere. I will systematically vary the properties of the lithosphere and impinging plumelets, mapping out how the coronae structures change with changes in the lithosphere and plumelet geometry as well as lithosphere and plumelet material properties. This would provide critical guidance for the VenSAR data products necessary to refine the science objectives and requirements.
To map the geodynmic output directly to the VenSAR data products, I will develop a tool that will calculate synthetic radar products from the model topographic and strain-rate maps producing model output products that are directly comparable with the anticipated radar products. This tool will be open source and well documented, following the CIG software best practices (geodynamics.org) for community software development and will be tested with both ASPECT and CitcomS (the two open-source, spherical mantle dynamics codes supported by CIG). This tool will be available to any researcher through the github repository at CIG. By providing geodynamic model data products that will test specific formation hypotheses, I will be able to:

- Help refine the VenSAR instrument's scientific objectives and requirements to achieve the EnVision mission objectives;
- Identify target areas on Venus for VenSAR observations;
- Help define the scientific data products required to achieve VenSAR objectives, including identifying any preliminary work required to create these products;
- Provide guidance for the development of VenSAR calibration and validation plans; including consideration of the following: the accuracy and precision of measurements based on instrument characteristics; orbit and attitude determinations; surface topography and reflectivity; other interactions with the atmosphere and other land and surface features; and any other relevant factors;
- and, Contribute to other VenSAR-instrument planning activities and science planning for EnVision as necessary, including identifying and performing geodynamic studies to support VeST tasks and contributing to the development of review materials and white papers.

The proposed work would help to refine the VenSAR instrument's scientific objectives and requirements which would benefit the EnVision mission and thus benefit NASA. By providing synthetic VenSAR output from convection calculations this work will inform specific formation mechanisms, helping to understand the specific observations, geometries, and resolution that will be needed to confirm or rule out specific formation mechanisms and/or lithosphere/mantle properties. This will significantly advance our understanding of these key Venus features. With over 30 years of experience in geodynamic modeling, I have the background to significantly contribute to the understanding of VenSAR observations and the understanding of how to combine

VenSAR observations with the other scientific intstruments on Envision: the subsurface radar sounder, UV and IR spectrometers, and radio science.

Alice Le Gall/Ctre Nat De La Recherche Scientifique
Investigating Venus' geological history and activity with VenSAR radiometry

VenSAR is a multi-mode instrument; in addition to its active modes of operation (SAR, altimetry), it includes a passive, or radiometry, mode. As a radiometer, VenSAR will record the thermal emission from Venus' surface at 3.2 GHz (9.5-cm wavelength) i) at a global scale with a nadir or near-nadir viewing geometry and, ii) in some targeted areas, at high incidence angle in H&V polarizations. The goal of this proposal is to use VenSAR radiometry dataset to address EnVision key science objectives, in particular providing clues on the surface properties (composition, density), alteration mechanisms (especially in highlands) and possible current volcanic activity. To that end, synergy with VenSAR active dataset and VenSpec-M observations will be essential.

The primary data product of VenSAR radiometry measurements will be a global map of Venus 9.5-cm surface brightness temperature readily convertible, provided assumptions on the surface physical temperature, into a map of Venus 9.5-cm nadir emissivity. Such map will be displayed at a finer spatial resolution than that derived from Magellan data (better than 10 km using all overlapping observations against 20 to 80 km for Magellan) and with significantly better precision and accuracy. The microwave nadir emissivity of a surface being largely controlled by its dielectric constant, a dielectric map will be inferred from the emissivity map thus providing insights into the surface bulk composition and density and a tool - complementary to SAR imaging and polarimetry - to distinguish and characterize geological units on Venus.

VenSAR radiometry, combined with EnVision topography data, will also be key to investigate an enduring puzzle about Venus: the surprisingly low microwave emissivity of some (but not all) highlands. Low emissivity suggests the presence of unusual minerals possessing a very high dielectric constant which could be due to the cold trapping of exotic volatile species, or yet unidentified weathering reactions. However, low emissivity could also be indicative of a low-loss substrate of moderate dielectric constant but where volume scattering dominates. For the first time with EnVision, polarized radiometry measurements performed in selected high altitude terrains will enable us to discriminate between these two hypotheses and directly measure the local dielectric constant and degree of volume scattering. Such investigation of Venus highlands as well as of e.g., impact modification in crater ejectas will shed light on chemical weathering and erosion mechanisms at play at the surface of Venus.

In addition to emissivity anomalies, VenSAR used as a radiometer will search for thermal anomalies as a proof of a current volcanic activity on the planet. On Venus, the optically-thick atmosphere strongly challenges the detection and monitoring of volcanism in the optical and near-infrared domains. Microwave radiometry has thus been proposed as a mean to detect hotspots". Furthermore, microwaves also offer the prospect of sensing the shallow subsurface and thus may detect warmth from old lava flows i.e., lava flows which have cooled at the surface and thus have no more infrared emission signature but are still hundreds of Kelvins above ambient at depth. VenSAR radiometry measurements will thus be highly complementary to VenSpec-M measurements; both will search for regions of either anomalously high thermal emission or showing temporal variations within the mission time or since Magellan.

As a former member of the SST (2018-2021) appointed by ESA to provide guidance on all scientific aspects of the EnVision mission during the Study Phase, I have an in-depth knowledge of the mission scientific objectives and in particular of VenSAR requirements to achieve these objectives. As an associate member of the Cassini Radar team (NPP 2008-2011 at JPL), I have worked extensively with radar and radiometry data. I here propose to place my expertise in service of the VenSAR team.

Zhong Lu/Southern Methodist University, Inc
Studying Volcanic Processes and Atmospheric Changes from VenSAR and Magellan SAR Imagery

I propose to study volcanic processes and atmospheric changes from VenSAR and Magellan synthetic aperture radar (SAR) imagery. My primary scientific objectives include (1) the mapping of volcanic processes using repeat digital elevation models (DEMs) from VenSAR and feature tracking of VenSAR and Magellan SAR images, (2) the study of surface changes based on calibrated SAR backscattering coefficients, and (3) the study of the changes in atmosphere conditions using feature tracking of repeated VenSAR and comparison with Magellan. I have accumulated 25 years of experience on studying Earth's volcanoes in the U.S. and worldwide with SAR images of various wavelengths from a diverse range of SAR missions, and have produced ~50 journal publications and a 390-page book on mapping, modeling and interpreting volcanic deformation and volcano changes using both SAR phase and intensity images and SAR-derived DEM. Serving the NASA-ISRO SAR (NISAR) Science Team from 2013 to present, I have gained extensive experience on the development of SAR processing algorithms, validation of SAR measurement error models, SAR product calibration and validation, and development of Algorithm Theoretical Basis Document (ATBD), white papers and SAR User Handbook. Hence, I propose to contribute my knowledge on the processes of Earth's volcanoes with SAR images, demonstrated research record, expertise on SAR techniques and SAR measurement error models, and decade-long experience on NISAR Science Team to help provide scientific feedback to VenSAR development as part of the EnVision VenSAR Science Team (VeST).

Philippa Mason/Imperial College of Science Technology & Medicine
Philippa Mason's proposal to become a non-US member of the VenSAR Science Team

This proposal contains evidential support for my application to become a non-US member of the VenSAR Science Team (VeST). It concisely presents my skills, experience, current and planned research activities over the next ~5 years, and how these contribute to the expected VeST activities and objectives.

Having been excited and passionate about science and space science since childhood, the opportunity to get involved in the EnVision mission proposal some 10 years ago, was too good to miss and, now that the mission has been selected, I am even more eager to support its development over the coming years. I am an Earth Observation (EO) geologist and currently a Senior Researcher in Planetary Remote Sensing, in the Department of Earth Science & Engineering, Imperial College London. I am a mature scientist with 30 years of experience as a geologist, and 23 as a remote sensing specialist, an active researcher in the development and application of remote sensing in exploration geoscience, in using Synthetic Aperture Radar (SAR) data and, over the last ~10 years, in the use and development of Interferometric SAR (InSAR) and Persistent Scatterer InSAR in ground deformation monitoring. I am a well-respected scientist of international renown, and am widely published in Earth Observation science, as well as in Venus science.

I was a core member of the EnVision mission proposal team at ESA M4 and M5 and, as a member of the original VenSAR team, was involved in the design discussions of the VenSAR instrument with the radar engineering team at Airbus UK, from 2010 onwards. In Sept 2018, I was appointed to the ESA Science Study Team (SST) and was funded by the UK Space Agency, (UKSA). I also served as a member of the Yellow Book (YB) Editorial Board. In Nov 2021 I was appointed by ESA as a member of the SST for Phase B1 (and am again funded by UKSA for that period).

During Phase B2 (2024-2027), I will undertake and oversee research focused on the development of simulated VenSAR geomorphology image products and the tools needed to produce them, and on the development of improved Venus atmospheric correction models and phase screen to optimize SAR processing for the Venus environment (to be funded by UKSA). During the course of the Phase B1 VenSAR Science Team study, I will devote my multi-disciplinary experience and expertise to assist and collaborate in VeST activities, as and when necessary.

Matthew Pritchard/Cornell University
Optimizing VenSAR observations to reveal the geologic history and activity of Venus informed by decades of terrestrial remote sensing

Venus is the closest planetary kin to the Earth in terms of size and current activity, but why its tectonic activity and atmosphere are so radically different from the Earth remains a mystery. The EnVision mission will dramatically improve our understanding of the enigmatic geologic history and current activity of Venus, especially the VenSAR instrument -- a Synthetic Aperture Radar (SAR) S-band (9.4 cm) radar instrument that greatly expands on the capabilities of the Magellan S-band radar that orbited Venus in the early 1990s. Over the past three decades, although no SAR missions have flown at Venus, there have been dozens of civilian SAR satellites and airborne systems that have collected data spanning a range of wavelengths, polarizations, and spatial and temporal resolutions.   As a member of VenSAR Science Team and the EnVision Science Study Team, the PI will leverage knowledge gained with SAR and other satellite data from Earth to better contextualize and exploit the data that will become available in the coming years from Venus. One question he will address is which areas of Venus would most benefit from having the dual polarization, high spatial resolution, or stereo coverage from VenSAR to address the EnVision science objectives regarding the history of magmatic, tectonic, and surface processes? For example, modern terrestrial SAR data span spatial resolutions from less than 1 meter/pixel to dozens or even hundreds of meters/pixel with multiple polarizations and the PI has decades of experience working with these datasets. The PI will compare these different spatial resolutions at terrestrial analog landforms to assess where the different VenSAR modes are needed. Although terrestrial S-band data similar to VenSAR have to date been very limited, one exciting new openly available dataset is the high spatial resolution airborne testbed for the NISAR (NASA-Indian Space Research Organization SAR) satellite called the Airborne SAR (ASAR) that includes both S (9 cm radar wavelength) and L (24 cm radar wavelength) bands. Observations from X- (~3 cm wavelength), L-, and C-band (~5.6 cm wavelength) radars with similar look angles, polarization, and spatial resolutions to VenSAR will also be used.   Another important question is what VenSAR imaging modes, complemented by other EnVision instruments, are needed to assess surface change on Venus during the EnVision and VERITAS missions and since Magellan? The PI will use his experience with multi-platform SAR and multi-spectral observations from Earth to help optimize data collection to detect and quantify surface change from volcanic, tectonic, and aeolian activity and mass wasting. The increasing flood of radar data available for the Earth from NISAR and international satellites will help optimize the collection of the new Venus SAR data that will become available in the coming decades.

Gregor Steinbruegge/Jet Propulsion Laboratory
Radar Geodesy and the Interior Structure of Venus

One of the top-level science priorities listed in the EnVision yellow book is to constrain Venus' internal structure as well as to constrain the properties and thicknesses of Venus' crust, mantle, and core. Geodesy is a fundamental asset in inferring the interior structure of planets as has been proven by previous missions. I propose to address the following three objectives:

1) I will refine the VenSAR instrument's scientific requirements to allow for constraints on Venus' geodetic reference frame and internal structure.
2) I will work on tour evaluation and contribute to science planning activities

3) I will perform interior modelling to obtain a better understanding on the accuracy individual geodetic parameters need to be measured to determine the thicknesses of Venus' crust, mantle, and core.

VenSAR has the capability to make use of globally distributed VenSAR altimetry data and ground-track intersections (cross-over points) to create a dense geodetic net. These observations can be used in concert with gravity observations and SAR images to improve the a posteriori orbit determination, to solve for the rotation state of Venus including spin axis orientation and precession, and to allow the co-registration of other data products generated by the EnVision mission via improving the overall reference frame of Venus. The precise measurement of the rotation state allows to infer constraints on the interior structure (e.g., by inferring the moment of inertia) as has been recently demonstrated by ground-based radar observations (Margot et al. 2021). As outlined in the yellow book, VenSAR will acquire a global network of altimetry mode tracks with a vertical resolution of 2.5 m, providing a far better constraint than any previous dataset. This data can be combined with control point networks from overlapping imaging data. To achieve the objectives listed above, I propose to (1) contribute to the development of altimetry algorithms and the evaluation of the predicted precision and accuracy of VenSAR altimetry; (2) propose to work on a procedure for geodetic reference frame development and control point networks; (3) use the SPICE kernels to analyze proposed EnVision orbit designs based on the impact for VenSAR; and (4) contribute new geophysical models able to investigate the interior structure of Venus based on the mean density and moment of inertia, and as a function of the interior composition and temperature.

Geodesy is an inherently multi-investigational science and my related expertise has multiple synergystic relations to other investigations. To understand the interior of Venus, a combination of multiple geodetic constraints will be necessary, including the gravity field, spin-axis orientation, and tidal Love number k2. The proposed work will benefit all instruments and assure that VenSAR requirements allow EnVision to produce first-class geodetic products.

Jennifer Whitten/Tulane University, New Orleans
Building Bridges: Merging VenSAR Scientific Objectives and Observations with Previous Mission Results

I will contribute to the VenSAR Science Team (VeST) in a variety of ways. Proposed activities that I could contribute to strongly as a member of VeST include:

- “Identify target areas on Venus for VenSAR observations;
- Contribute to other VenSAR-instrument planning activities and science planning for EnVision as necessary, such as:
    - Assist in the & evaluation of simulated VenSAR data for the regions of interest as described in the EnVision Yellow Book;
    - Identify and potentially perform necessary studies or analyses to support the VeST tasks, and or evaluate such studies when completed;

    - Contribute to the development of review materials and white papers as required; and
- Ensure that all synergistic and multidisciplinary science to be enabled by combining VenSAR with EnVision's other instruments, as well as other Venus missions, is considered in VenSAR development."

I am uniquely qualified to serve as a member of EnVision's VeST. As the Associate Deputy Principal Investigator for VERITAS, I have an intimate working knowledge of that mission, its scientific objectives, and data products. I am also a member of the Venus Subpanel of the National Academics Planetary Science and Astrobiology Decadal Survey 2023-2032. These experience are particularly relevant to this VenSAR proposal call, as I can provide insight into how EnVision VenSAR measurements can complement VERITAS observations, and where VenSAR can improve on measurements and data products. I am leading the VERITAS search for change detection in SAR data, specifically focused on the search for new volcanic flows", though surface from other processes will be search for as well. Other research and mission experiences (Moon Mineralogy Mapper, MESSENGER, SHARAD) have provided me with the expertise to meaningfully contribute to the VeST team.

Program Relevance: The proposed effort would support VeST and the EnVision mission and science objectives, as described in the proposal call. My research interests and past experiences engaging with Venus data and the VERITAS mission are preparing me to help "identify target areas…for VenSAR observations", "contribute to other VenSAR-instrument planning activities and science planning for EnVision", and contribute to ensuring "all synergistic and multidisciplinary science…is considered in VenSAR development".

Volatiles Investigating Polar Exploration Rover Co-Investigator 2021 Program
Abstracts of Selected Proposals
(NNH21ZDA001N-VIPER)

Below are the abstracts of proposals selected for funding for the Volatiles Investigating Polar Exploration Rover (VIPER) Co-Investigator 2021 Program. Principal Investigator (PI) name, institution, and proposal title are also included. 50 proposals were received in response to this opportunity. On December 15, 2021, eight proposals were selected for funding.

Barbara Cohen/NASA Goddard Space Flight Center
VIPER Measurements of Nitrogen and Noble Gases in Polar Regolith

Science Goals: The objective of this proposal is to use MSolo to assess the nitrogen and light noble gas (He, Ne, Ar) content and isotopic makeup of volatiles collected by VIPER to understand the surface exposure and geologic history of the lunar exosphere, polar regolith, and volatile deposits. These data will be used to understand the surface exposure history, gardening rate, and origin of volatiles encountered by the VIPER mission during traverse and drill operations. These measurements will give crucial context to planned stable-isotope measurements (H, O) of volatile and organic compounds measured by the mission, as well as help more completely determine the origin of volatiles in different lunar reservoirs investigated by VIPER.

Methodology: The planned VIPER investigations already include isotopic measurements of H (as D/H ratio) and O (as 18O/16O ratio). I propose to extend the range of isotopic measurements using MSolo to the stable isotopes of N and the noble gases He, Ne, and Ar. Nitrogen trapped in the lunar regolith presents a highly variable isotopic composition, which represents different contributions from light solar wind and heavy planetary sources (meteorites, micrometeorites, comets) are enriched in the heavy isotope of nitrogen. Noble-gas isotopic ratios and abundances provide important constraints on the amount and history of the solar wind and cosmic ray exposure record, indigenous degassing, and impact processing of the lunar surface. As MSolo scans through its range, I will focus on abundance measurements of the nitrogen and noble gases as a function of activity type (e.g., stationary, roving, drilling) and isotopic ratio measurements as a function of geologic setting (e.g., temperature, surface depth). I will work with the MSolo instrument team to identify operational modes and potential new modes for noble-gas abundance and isotopic ratios. I will also work with the other VIPER instruments and teams to determine the chemical composition, mineralogy, and petrology of the regolith, which is another dimension adding to the geologic interpretation.

Relevance: Understanding the composition, quantity, distribution, and form of water and other volatiles associated with lunar permanently shadowed regions (PSRs) is identified as a Strategic Knowledge Gap (SKG) for NASA's human exploration program, projected to visit the lunar south pole in the next decade. These polar volatile deposits are also scientifically interesting, having potential to reveal important information about the delivery of water to the Earth-Moon system. Parameters derived from nitrogen and noble gas isotopic ratios will provide essential context to the VIPER measurement requirements as well as other studies of the lunar polar regolith. These measurements would significantly enhance the capability of VIPER to distinguish the components contributing to lunar volatile reservoirs (planetary, solar wind, indigenous outgassing, etc.) as a function of VIPER's mission parameters of location, depth, and temperature. I am also committed to a significant investment in VIPER and MSolo operations for both the PI and a postdoc, supporting the project in operations roles throughout mission development and operations.

Masatoshi Hirabayashi/Auburn University
Statistical and Thermal Approaches to Constrain the Impact-Induced Regolith-Volatile Distribution Mechanisms

Participating in the VIPER mission, the planned project will explore the following major science question (MSQ): How do impact-driven mixing processes contribute to the evolution of the water ice distribution in subsurface layers (from surface down to 1 m depth) on the Moon? This project will employ a modeling approach that accounts for both impact-driven mixing and thermal conditions to constrain the effects of impact-driven mixing on the water ice distribution. This model will incorporate the following mission-derived measurements: subsurface temperature profile, subsurface water ice distribution, and surface topography. If possible, surface temperature profiles will also give useful information to the planned analysis.

To address MSQ, we define the following science objectives:
- (SO.1) Constrain the water ice distribution in subsurface layers at a science station: Apply measurement data at a single science station and employ a modeling approach to find how the water ice distribution has evolved at this site.
- (SO.2) Analyze the water ice cycle evolution in subsurface layers at multiple science stations: Integrate data from multiple science stations and quantify how much water ice has been supplied and mixed over time.
- (SO.3) Quantify how impact-driven mixing has contributed to the water ice evolution in subsurface layers on the Moon: Constrain how efficiently impact-driven mixing contributes to the water ice distribution in subsurface layers.

To achieve the SOs, we plan the following four tasks:
- Task A: Make our multi-physics model ready for the planned analysis: Establish a multi-physics approach integrating a model of impact-induced mixing and that of thermal migration by incorporating missing model functions.
- Task B: Convert the temperature distributions at subsurface assay sites to those at a science station: Use a 3-dimensional (3D) thermal finite element model (FEM) to

characterize the temperature distributions at subsurface assay sites and apply the 1-dimensional (1D) thermal FEM to model the thermal condition over each science station.
- Task C: (SO.1, SO.3) Characterize the water ice redistribution cycles within a single science station: Integrate measurement data within a single science station and our model to constrain the evolution of the water ice distribution there.
- Task D: (SO.2, SO.3) Quantify the role of impact-inducted mixing in water ice supply and redistribution over the VIPER investigation site. Use results from Takes B and C to characterize impact-driven mixing and quantify how efficiently it contributes to the water ice distribution over all the planned science stations.

Expected contributions from the current project will include better characterizing the influences of impact-driven mixing on the water ice distribution and its origin and evolution. By this, the project will directly address VIPER's primary objectives: characterizing the distribution and physical state of water and other volatiles in lunar cold traps and regolith and evaluating the potential return of In-Situ Resource Utilization (ISRU) from the lunar polar regions [Proposal Information Package (PIP), 2021]. Also, recent reports specify that it is critical to characterize interactions between water ice and regolith [Visions and Voyages: Planetary Decadal Survey, 2013; Scientific Context Exploration of Moon, 2007; Advancing Science of the Moon; NASA's Strategic Knowledge Gaps, 2016]. The Science 2020-2024: A Vision for Science Excellence also states that the NASA Planetary Science strategic objective is to advance scientific knowledge of the origin and history of the solar system. The project will successfully address these Planetary Science questions and goals. Furthermore, by actively joining planned activities through the mission, we will contribute to VIPER's success.

Laszlo Kestay/USGS Flagstaff
Ground Truth for Lunar Resource Assessments

The VIPER mission has two primary objectives: (1) Characterize the distribution and physical state of lunar polar water and other volatiles in lunar cold traps and regolith to understand their origin and (2) Provide the data necessary for NASA to evaluate the potential return on in-situ resource utilization from the lunar polar regions. The proposed work would be directly relevant to both of these objectives. Task 1 focuses on testing the hypothesis that there are young water ice deposits that are associated with specific times in the Moon's geologic history (i.e., water-rich impacts). Using classical geologic mapping methods and stratigraphy, those specific times will be identified. This information can then be translated into specific locations on and within the entire Moon. Testing this hypothesis, even if it proves incorrect, will significantly advance our ability to predict the distribution and physical state of ice and other volatiles in the lunar polar regions. Task 2 would obtain a key geotechnical parameter (angle of repose) needed to evaluate different resource processing technologies and thus help determine how much of the lunar ice is technically recoverable and help determine the cost of developing the needed technology. Evaluating the cost of converting the ice into a useful commodity is a required to convert a technically recoverable resource into a reserve. Task 3 and Task 4 will provide unique perspectives and expertise for operations and archiving, working to help VIPER create the best possible data set for the benefit of the whole international lunar exploration community.

Kestay will be responsible for all tasks in this proposal and fully comply with both the spirit and letter of the VIPER Rules-of-the-Road and all relevant NASA (and USGS) rules and regulations. This includes ensuring that any collaborators that may join also fully comply with the VIPER Rules-of-the-Road. The PI of this proposal has access to all the computer hardware and software required to complete the proposed tasks. Sufficient time is requested to fully participate in VIPER team activities related to operations and data archival. The proposed work is not strictly tied to any single instrument or science theme. Task 1 (lunar ice geologic model) could readily fit under the Modeling and Mapping" theme but is actually slightly better aligned with the Geologic Context" theme because of its strong focus on stratigraphy and timing which fits under the Chronology" subtheme. Task 2 could be considered "Regolith Science" under "Environments." Task 3 is squarely in "Science Operations & Integration" while Task 4 is under "Data Management." In terms of instruments, the work proposed here relies most directly on NavCam and HazCam images but will utilize information from all instruments. Risks will be carefully managed to ensure that the efforts proposed here will increase the success of the VIPER mission.

Myriam Lemelin/Universite de Sherboroke
Unmixing the Spectral Variations of the South Polar Region to Retrieve its Composition, Volatile Content, Sources and Modification Processes

The goal of the proposed work is to refine our understanding of the composition, volatile content, sources, and modification processes occurring in the south polar region, both inside and outside cold traps using the spectral measurements acquired by the Near InfraRed Volatiles Spectrometer System (NIRVSS). The objectives are to (1) understand the respective contribution of solar wind and micrometeorites in the current volatile cycle, (2) understand the respective contribution of solar wind and micrometeorites in the space weathering process, (3) characterize the regolith porosity inside and outside cold traps, and (4) compare the local mineralogy, volatile content, and space weathering information from NIRVISS to the regional information from orbital measurements.

The first two objectives will be addressed by deriving a radiative transfer model that can account for the presence of known minerals in the polar regions (plagioclase, pyroxenes, olivine, hematite), minerals that could come from exogenic sources, volatiles, regolith constituents arising from space weathering (agglutinates, microphase iron and nanophase iron) and surface porosity. This radiative transfer model will be based upon equations from the Hapke model and laboratory observations. The radiative transfer model will be applied to NIRVISS observations to provide real time information on volatiles, mineralogy and space weathering. The third objective will be addressed deriving an automatic grain size and porosity measurement using images acquired by the AIM. The porosity measurement derived from the AIM will be integrated into the radiative transfer model when analyzing real time NIRVSS data. This will allow to quantify the regolith porosity inside and outside cold traps and potentially confirm the presence of the fairy-castle structure. The fourth objective will be addressed by filling the data coverage gap that exist in the currently mapped polar mineralogy, volatile content, and space weathering products, that is the information within PSRs. This information will be obtained as points" of data by the NIRVISS instrument along its traverses. We will test traditional geostatistical interpolation methods and multi-resolution spatial models to determine which one provides the best results. This will allow to provide regional information at a finer spatial scale than the current remote sensing observations, which will be a valuable tool to understand the mineralogy, volatile content, and space weathering products and assess potential resources.

The results from the second and third objective will be compared to a similar investigation that will be conducted by the Lunar Vertex mission. As a Co-Investigator on the Lunar Vertex mission going to Reiner Gamma in 2023, I will be involved in the study of space weathering and regolith properties. The magnetic anomaly at Reiner Gamma likely deflects solar wind protons which leads to a reduced degree of solar wind-derived space weathering products, much like is anticipated in the polar regions and in cold traps.

Overall, the proposed work would allow to address the two primary objectives of the VIPER mission. The use of data from other orbital and landed missions will bring added value to the data generated by VIPER. The use of data generated be VIPER will in turn allow to validate orbital based remote sensing measurements and prepare for the interpretation of data acquired by upcoming remote sensing missions.

Kevin Lewis/Johns Hopkins University

A Geophysical Traverse at the Lunar South Pole with the VIPER Accelerometers

Science goals and objectives: Gravimetry is a standard tool for analysis of subsurface structure on the Earth. On the Moon, the Apollo 17 mission conducted the only surface gravity traverse to date, over several kilometers across the Taurus-Littrow valley with the Lunar Traverse Gravimeter Experiment (TGE). Recently, Lewis et al. [2019] demonstrated the ability to calibrate the Curiosity rover Inertial Measurement Unit (IMU) accelerometers to derive gravity data on the surface of Mars. These data were of sufficiently high precision to estimate the subsurface porosity of Mount Sharp along the rover traverse, providing constraints on the geologic history of the landing site. We propose to use the IMU accelerometers onboard VIPER to collect gravity measurements along the rover traverse. By evaluating variations in the strength of the gravitational acceleration, we will be able to detect variations in subsurface density arising from porosity, material changes, and buried subsurface structures These surface gravity data will be significantly higher spatial resolution than is obtainable from orbit, which is limited to ~5 km resolution. We will additionally use the IMU accelerometers for active seismic exploration of the subsurface during TRIDENT drilling operations. These seismic data, particularly during rover drilling, could reveal useful information about shallow subsurface structure and volatile content, complementing other rover analyses of the near subsurface.

Methodology/Data to be used: This investigation will utilize data from the rover IMU accelerometers along with other engineering data, including rover temperature sensors. The proposed investigation does not require novel modes of operation for engineering sensors, require only minimal data volume, and poses no meaningful risk to the IMU or other sensors. Gravity data will be combined with topography derived from both orbital and rover navigation cameras to analyze the gravity signature arising from the subsurface. The investigation team will work together with other members of the rover team to enhance scientific return from the rest of the payload, and to enhance other scientific modeling efforts that require knowledge of subsurface structure and physical properties.

Relevance of the proposed research to VIPER: This investigation will enhance the return of the VIPER mission by deriving additional scientific products from engineering data. Gravity data will help in understanding the porosity and heterogeneity of the lunar regolith with depth, which is an essential input to thermal, structural, seismic, volatile transport and other models central to the goals of the VIPER mission. Seismic data will help constrain the presence and distribution of ice in the subsurface. This investigation makes use of an unplanned rover capability, and would collect, calibrate, and archive data that would otherwise likely not be acquired.

Personnel: Kevin Lewis (PI) is an Associate Professor at Johns Hopkins University (JHU) and will oversee the project and lead the calibration of the VIPER accelerometers for gravimetry. Lewis is an expert in planetary topographic analyses and pioneered the calibration of the Curiosity rover accelerometers to conduct the first surface gravity traverse on Mars. A JHU postdoc will conduct gravity analyses with the calibrated accelerometer data in combination with orbital and rover-derived topography data. Co-I Nicholas Schmerr is an Associate Professor at the University of Maryland, and will lead the evaluation of accelerometer data for seismic studies in collaboration with the postdoc. Dr. Schmerr is an expert in lunar seismology whose expertise is essential for this portion of the proposed work.

Kathleen Mandt/Johns Hopkins University
Tracing Lunar Volatile Sources Based on Composition

The composition and abundance of volatiles stored within Ice Stability Regions (ISRs) of the lunar south pole are not only of great interest for human exploration, but also for understanding volatile history in the Earth-Moon system. Although five potential volatile sources have been identified, the relative contribution of each source is not known. Measuring isotope ratios, noble gases, and abundances of carbon-, nitrogen-, and sulfur-bearing species will advance our understanding. Our recent re-analysis of the Lunar Crater Observation and Sensing Satellite (LCROSS) observations, outlined in Section 2.2, provides a useful framework for approaching analysis of future measurements by VIPER. My goal, if selected as a VIPER Co-I, is to advance our understanding of the origin of lunar volatiles using VIPER volatile composition measurements, and to support the MSolo team as needed with mission operations, data analysis, and data archiving.

To achieve this goal, I will work with the VIPER team to answer the following questions:

Q1. What is the bulk elemental and isotopic composition of volatiles found in the regions explored by VIPER?

Q2. How does the bulk elemental and isotopic composition vary spatially and with depth in all areas explored by VIPER?

Q3. What volatile sources could have contributed to each observation and what does this mean for lunar volatile history?

To answer these questions, I will work with the VIPER Mass Spectrometer Observing Lunar Observations (MSolo) team, contributing my experience with lunar volatile research and lessons learned from working with data obtained by the Cassini Ion Neutral Mass Spectrometer (INMS) and a commercial off the shelf (COTS) Cave Mass Spectrometer (CMS). If selected, I will work with the team to gain a detailed understanding of the instrument and planned analysis tools, to contribute to preparing additional analysis tools, to plan measurements prior to and during the mission, and to conduct detailed analyses of the observations. I will also assist with the production of data products that will be submitted the NASA Planetary Data System (PDS). These goals will be realized by achieving four science objectives that are designed to answer the science questions as illustrated in Fig. 1:

A. Develop a method for identifying species observed by MSolo and for determining their composition relative to water.

B. Define the observation strategy for taking measurements needed to answer Q1-3.

C. Determine the elemental abundances and isotope ratios from MSolo observations.

D. Connect observations to source materials.

If selected for this opportunity I hope to be able to advance the science return of the VIPER mission by helping to obtain the greatest scientific value from the MSolo observations through detailed analysis of the mass spectra, by assisting the VIPER team in providing valuable data products to the PDS for broader community use, and by connecting the observations made by VIPER to the general question of the role of lunar volatiles in solar system formation and evolution. The outcome will be enhanced science return for the mission and linking the science achieved by this mission to broader NASA goals that have implications not only for lunar science but also for solar system formation and evolution.

Noah Petro/NASA Goddard Space Flight Center
Comparing the Exchange of Water and Methane with the Lunar Surface and Exosphere

It is now well established that water and other volatiles exist on the surface of the Moon. Since 2008 our understanding of volatiles has dramatically shifted, however, we are only beginning to understand how volatiles are sourced, transported, and retained on the Moon. The exchange of volatiles with a surface is dictated by the strength of the bond between the surface and the molecule, but the Moon's surface is an extremely complex arrangement of surfaces with wildly varying attraction to individual molecules. We can understand the net behavior of the lunar surface by probing it with two molecules of very different volatility: methane and water. Using these two distinct volatiles, an understanding of the chemical processes occurring on the surface of the Moon will be gained along with timescales on which these volatiles are stable on different surfaces of the Moon. Measurements of the behavior of water and methane on different surfaces that are illuminated and shadowed on different timescales enables this comparative study.

In this proposal we will investigate the residence time of volatiles after condensing onto cold lunar surfaces, determine the relative variations of water and methane over diurnal timescales at high latitudes, determine the role of micro cold traps and shadows at retaining water and methane, and study the effect of space weathering on lunar volatiles within permanently shadowed regions. All these objectives aim to characterize the range of activation energies and residence times of molecules on the surface to allow for better modeling of volatile deposits around the Moon. To address these objectives, we will use the NIRVSS and MSolo instruments to measure the abundance of water and methane under varying conditions. We will also make use of the tungsten filament lamp to perform heating experiments on the surface of the Moon to understand how these two volatiles behave with temperature allowing for us to extrapolate VIPER data at high southern latitudes to a global context.

We also provide Earth-based data at wavelengths similar to NIRVSS (1.5 to 4.2 microns) and independent measurements of water using the NASA Infrared Telescope Facility (IRTF) and the NASA Stratospheric Observatory For Infrared Astronomy (SOFIA), respectively. Data from both observatories has been collected and is available to the public. By comparing the 3 micron band observed by VIPER to that of the ground-based 3 micron band we can place VIPER measurements into regional context at locations beyond the landing site and traverse path of the rover. Comparing VIPER to Earth-based data will act as a link between remote sensing observations and ground truth measurements. With SOFIA we observe a new spectral region for the Moon from 5 to 8 microns that contains a water only signature at 6 microns. Unlike the 3 micron band that can be created by hydroxyl and water, the 6 micron band is strictly due to water. With observations of high southern latitudes in hand we can provide a constraint on how much water is present. This allows the 3 micron water to hydroxyl ratio to be estimated and provides better constraints on the relative amounts of hydration phases present at VIPER locations.

The study proposed here is directly applicable to the overall science objectives of VIPER. This proposal directly addresses decadal survey question 'What governed the accretion, supply of water, chemistry, and internal differentiation of the inner planets and the evolution of their atmospheres, and what roles did bombardment by large projectiles play?' and 'How have the myriad chemical and physical processes that shaped the solar system operated, interacted, and evolved over time?' This proposal aims to understand how volatiles exchange with the lunar surface and how they are stored and transported around the Moon. This understanding of volatile storage and exchange on the Moon can be applied to other airless bodies in the solar system like asteroids.

Parvathy Prem/Johns Hopkins University
Modeling Active Volatile Sources and Transport During the VIPER Mission

During its mission, the Volatiles Investigating Polar Exploration Rover (VIPER) will interact with a microenvironment that is shaped by a number of active processes, including volatile transport and micrometeoroid bombardment. These processes are thought to operate on observable time scales and, over much longer time scales, contribute to writing the geological record at the lunar poles. Understanding active processes is thus critical to characterizing the distribution, origin, and resource potential of lunar polar volatiles. This proposal aims to enhance the science return of the VIPER mission by modeling volatile sources and transport processes that may be active during the mission, particularly lander exhaust, potential sublimation from drill cuttings, and micrometeoroid vaporization of nearby cold-trapped ices.

Understanding the fate of exhaust gases released during descent and landing is particularly important for a volatiles-investigating mission. Our recent modeling work, as well as Apollo-era measurements, indicate that lander exhaust can temporarily elevate local exospheric density by several orders of magnitude, deposit volatiles on cold surfaces, and persist in detectable quantities for several days. Crucially, exhaust gases can cover an area several kilometers wide, such that VIPER may spend most of its mission within the exhaust footprint of the Griffin lander. Due to low polar surface temperatures and the relatively long timescale for burial by impact gardening, adsorbed water may contribute to measurements of surface hydration by NIRVSS and MSolo during traverses. Exhaust gases often also include volatiles that may otherwise be indicators of cometary or volcanic origin.

Interpreting the magnitude of surface hydration and its correlation with surface mineralogy and sub-surface hydration requires understanding the relative contributions of various sources, as well as spatial and temporal variations due to volatile transport. The isotopic signature of volatiles, another important indicator of their origin, can also change during transport as heavier species are less rapidly dispersed.

The objectives of this work are: (1) To model the deposition and dispersal of exhaust gases released during landing, and assess their potential contribution to NIRVSS and

MSolo measurements of surface and exospheric volatiles over the course of the VIPER mission, in order to support mission planning. (2) To model the relative magnitudes and characteristics of other volatile sources that may be active during the VIPER mission, particularly sublimation of excavated volatiles from drill cuttings and micrometeoroid vaporization of pre-existing cold-trapped ices. (3) To integrate model predictions with NIRVSS and MSolo measurements during the VIPER mission in order to advance scientific understanding of how volatiles interact with the lunar surface, which in turn has important implications for resource renewability and accessibility.

The modeling tasks above would use a Direct Simulation Monte Carlo volatile transport code with proven capabilities, including the unique capacity to model the unsteady release and collisional gas dynamics of exhaust gases, as well as the ability to model small-scale surface temperature variations and the behavior of multiple isotopologues of water. The code will be adapted to incorporate high-resolution surface temperature maps and multiple volatile species of interest. Numerical simulations would use the Stampede2 supercomputer, to which the PI has access through the NSF XSEDE program.

This work would contribute to VIPER mission objectives of understanding the origins and evaluating the resource potential of lunar polar volatiles. These objectives in turn reflect priorities outlined in the Decadal Survey and the ASM-SAT and Artemis SDT reports. This proposal also responds to the VIPER Co-I Program's call for investigations related to modeling of volatile sources, sinks and transport".

Mars Science Laboratory Participating Scientist Program
Abstracts of selected proposals
(NNH21ZDA001N- MSLPSP)

Below are the abstracts of proposals selected for the MSLPSP program. Principal Investigator (PI) name, Science PI (if applicable), institution, and proposal title are also included. Fifty Step-2 proposals were received in response to this opportunity. As of January 26, 2022, 25 proposals were selected to support MSL Participating Scientists.

Laura Marie Barge/Jet Propulsion Laboratory
Investigating Abiotic Mineral-Organic Chemistry to Interpret Organic Detections on Mars

Background: The MSL Curiosity rover (SAM instrument) has detected organic matter in 3-billion year old mudstones at Gale Crater. The exact composition of the organics may include carboxyl groups, N-bearing groups, and organic-sulfur compounds. A variety of reactive minerals are present in the mudstones where the organic matter was detected, including iron oxyhydroxides, phyllosilicates, and iron sulfides. These organics are believed to be indigenous to Mars and so their source remains a significant question: Are these organics remnants of ancient biotic or prebiotic processes on Mars? (Addressed by Goal 1, below.) Even if the organics are ultimately abiotic, non-biological organic chemistry especially in aqueous, redox-active mineral-rich environments can give rise to a diverse array of prebiotic products, beyond what is observed in meteorites. Furthermore, abiotic organic chemistry in geological settings can give various product distributions depending on geochemical conditions, and these can be challenging to distinguish from biotic or prebiotic processes. Therefore, analog studies to understand the SAM organic detections must also address the question: Are these organics remnants of abiotic or prebiotic organic chemistry that was favored under ancient Gale crater lake redox and pH conditions? (Addressed by Goals 1 - 2, below.) In order to understand both a) the likely organics that are present in a sample analyzed on Mars, and b) the pathways that formed those organics in the first place on ancient Mars, several layers of lab analog analyses are necessary: from investigating abiotic organic reactions in an early Mars context, to analyzing such analog samples with SAM-like methods. We will work with the MSL and SAM science teams to utilize the outcomes of our laboratory experiments combined with ongoing mission operations and MSL science theme group involvement, to help give input into future SAM analyses on Mars, especially the remaining wet chemistry experiments (Goal 3, below). This is an investigation that would enhance the science return from SAM measurements of organics through&analog laboratory work with a focus on mineral/organic interactions, radiation transformation of organics, and the interpretation of GCMS wet chemistry data."

Science goals and Objectives: We will attempt to infer precursor organics from SAM-like lab analog data, and also, infer geochemical conditions under which those organics were likely to form in the first place helping to inform future organic analyses and wet chemistry experiments on Mars. This will be accomplished with 3 Science Goals. Goal 1: Determine which mineral components in ancient Gale Crater lake were most likely to drive in-situ organic reactions which could lead to the organics observed today. This will be accomplished via two tasks   Task 1: Create Mars analog organic/mineral samples relevant to Gale Crater with prebiotic precursors to organics that have been detected by SAM; and conduct lab experiments to determine which Mars analog simulants are most likely to affect organic reactions. Task 2: Determine mineral-driven organic product distributions as they relate to pH and iron redox state, under conditions relevant to Gale Crater. Goal 2: Determine how changes in oxidation state and pH in Gale Crater (including the effects of perchlorate and chlorate) correlate to MSL observations of organics. This will consist of two tasks   Task 3: Investigate the effects of perchlorate and chlorate on the organic reactions; Task 4: Analyze Mars mineral/organic analog samples of prebiotic organics with or without oxidant interaction with the SAM breadboard. Goal 3: Enhance the science return from SAM measurements of organics, and participate as a member of the MSL science team. This will be accomplished with Task 5: Operational support and iterating mission and experimental data to support MSL science objectives.

Laura Marie Barge/Jet Propulsion Laboratory
Science PI: Laura Rodriguez
Long-Range Tracking of CHONPS hotspots and Organic Compounds on the Martian Surface via ChemCam: Developing Novel Data Science Tools for Uncovering Hidden Molecular Signals

Background: ChemCam on the MSL Curiosity rover is capable of facilitating the search for life on Mars as it is equipped to do stand-off (< 7 m) Laser-Induced Breakdown Spectroscopy (LIBS), an analytical method that can identify organic and CHONPS hotspots strongly correlated with life. LIBS can simultaneously detect all CHONPS elements as well as small molecular signals including those produced from organic compounds. As LIBS is both rapid and stand-off, ChemCam is uniquely poised to identify organically-rich/astrobiologically-relevant targets and thus help inform mission operations (i.e., rover movement / sample collection for additional analyses (e.g. via SAM)). Notably, detecting organically sourced CHONPS on Mars via LIBS is difficult as interferants (e.g., Fe, minerals, water, CO2) can mask organic signals that are likely relatively depleted already. However, LIBS is sensitive to matrix effects, and this can be leveraged to discern the mineralogical and organic components using the right data science tools. The data science field is exploding with new machine learning (ML) techniques that have already proven fruitful for our ongoing work to elucidate mineralogical gradients in planetary sample analogs.

Science goals: The goal of this work is to develop a means to track organic/CHONPS abundance with ChemCam in an effort to discern organic trends with mineralogy and determine plausible sources of these materials. To this end the work is broken up into three objectives: (1) determine spectral features diagnostic of inorganic and organic CHONPS species; (2) determine potential for Martian organics observed are sourced from (A) endogenous abiotic chemistry; (B) exogenous delivery; or (C) derived from biological materials; and (3) Enhance MSL science return by developing a user-friendly application that enables rapid CHONPS and organic determination to inform mission operations in near real-time.

Methodology: ML models for characterizing CHONPS/organic content will be built by taking Mars-relevant minerals, specifically Fe(III) and Mn(II)-oxyhydroxides (synthesized in the lab) and spiking them with organic/inorganic CHONPS species as well as cellular materials. We will specifically test the impact of adding the mixture to the mineral matrix (e.g. adsorption in water vs. mixing of dried powders) to determine whether there are features indicative of how these materials were sourced. Samples will be analyzed using the ChemCam testbed at LANL. For ground truthing, samples will be sent to a third party analytical service providers for quantitative XRD, ICP-OES (for total P/S), elemental analysis (for total N/H/C), and C analysis (total/inorganic/organic C, graphite content).

Relevance: This work directly addresses MSL science objectives, determination of the mineralogy and chemical composition (including an inventory of elements such as C, H, N, O, P, S…of surface and near surface materials" as well as characterization of organic compounds and potential biomarkers in representative bedrock and regolith." Additionally, this work is relevant to MSL's desire to seek “investigations…that leverage expertise with chemical biosignatures and trace element indicators of environmental conditions using ChemCam LIBS data.” Additionally, the developed application will enable rapid determination of CHONPS inorganic/organic species in samples analyzed by ChemCam on Mars, which would enable the MSL team to identify regions most promising for observing organic materials via SAM. Lastly, we will participate in daily rover science operations and in a Science Theme Group as well as any other PS requirements.

Joseph Battalio/Yale University
Connecting Atmospheric Dynamics Across Many Scales at Gale Crater

Dust and water cycles on Mars are modulated by dynamics at many spatial and temporal scales. At local scales, dust devils lift a large percentage of dust from the surface, and gravity waves impact hydrogen loss. At larger scales, traveling waves modulate dust activity, globally impacting temperatures and transporting water. Thus, understanding the dynamics at each of these scales and their interactions is paramount; however, many aspects of the dust and water cycles are poorly understood.

Fortunately, MSL resides in an opportune location to observe large-scale waves with periods from seconds to weeks. MSL's location in Gale Crater also permits observations of the Aphelion Cloud Belt and gravity waves and has provided continual observations of dust devil activity. MSL's long observational record allows for analysis of inter-annual variability and interactions among wave types. The objectives of the proposed work are to link the atmospheric dynamics of phenomena at many spatial and temporal scales by providing a holistic view of atmospheric variability at a single location. Several topics will be explored: the source of long-period waves at Gale, the connection between gravity waves and observed cloud morphology, in-depth statistical and morphological analysis of dust devils, the interactions between waves at all scales, and the representativeness of the large-scale dynamics at Gale to other regions of Mars.

In-situ meteorological data, (pressure, temperature, humidity, and radiation) from the Rover Environmental Monitoring Station (REMS) will quantify the dynamics and timing of waves. These data will be compared to reanalysis datasets to generate a wave climatology, and their dynamics will be correlated to observations of dust opacity. Second, REMS data will also be compared to gravity waves observed by Mastcam and Navcam movies. This will allow for the determination of whether specific types of gravity waves are more likely to generate clouds observed by MSL. Third, comparison of dust devil vortex statistics in REMS pressure observations to REMS UV flux data will allow for basic opacity determinations of dust devils to help assess lifting amounts. Comparison of these features to Mastcam, Navcam, and Hazcam dust devil surveys will allow for quantification of dust lifting away from the rover. Finally, the near decade-long duration and reliability of MSL's surface observations makes the assessment of inter-seasonal and inter-annual variability possible. In controlling for this variability, more subtle interactions between scales can be examined to make simple forecasts of wave and dust activity using teleconnections and climatic modes of variability.

John Bridges/University of Leicester
From Clay to Salts: Evolution of Brines and Habitability Recorded in Gale Mineralogy

Curiosity is about to explore a region representing a transition from clay-dominated to sulfate-dominated lithologies as observed from orbit. This geological sequence is expected to record how environmental conditions and habitability on Mars changed as the type of fluid activity altered. Curiosity will be studying, for the first time on Mars, the terrains that could be the primary witness, the Rosetta stone, to the Hesperian climate change. Therefore, in the proposed work, we aim to use this unique opportunity to constrain this fundamental change in Mars' geological and mineralogical record by studying the rocks that will be encountered by the Curiosity rover up to 2025 as it traverses through the Gale Crater terrain called the Sulfate Unit in the next extended mission.

To achieve this, we propose four objectives that will use a variety of thermochemical modelling techniques based upon inputs from existing and new mineralogical and geochemical measurements by Curiosity to build a full picture of Gale Crater's water-rock interaction history, and its changing habitability through time. Objective one is to determine the key mineral assemblages and geochemistry of the Sulfate Unit from new data. This will aid data interpretation by the team, provide the input and context for our models and support interpretation of returned data for operations purpose. We will distinguish mineral assemblages and geochemical trends resulting from detrital input from those associated with secondary mineral assemblages formed within Sulfate Unit localities. Identifying detrital compositions will in turn enable new insights about sediment provenance and crustal differentiation, in particular the range of compositions in the sediment source regions. We will search for changes in provenance and alteration mineralogy in the returned data as Curiosity enters the Gediz Vallis channel. The second objective is to determine the conditions of water-rock reactions and resulting environmental conditions during alteration mineral formation. We will use thermochemical modelling to quantify the environmental parameters (P, T, X) that accompany the transition from clay-dominated alteration to sulfates, with decreasing water availability and changes in fluid chemistry. The Sulfate Unit modelling will require an emphasis on evaporation, low-temperature fluid boiling, freezing, and fluid-fluid mixing, none of which have yet been investigated in detail for Gale crater but will become very important in the Sulfate Unit. An expected fracture control on some key localities including the Boxwork terrain that Curiosity will visit means that we will use low-temperature fluid boiling models assuming a low atmospheric pressure environment. Our third objective is to quantify habitability within the studied environments by directly calculating available energy for a range of metabolisms known to thrive in terrestrial analog settings. We will use the results of our geochemical analysis and water-rock reaction characterisation as a robust basis to quantify habitability via calculation of energy budgets and the associated potential biomass that the paleo-environments could have supported. Our fourth objective is to participate regularly in ongoing rover operations and play an active role in the interpretation of the data during team discussions and meetings. We will also provide a novel contribution to strategic planning and selection of drill sites through developing a quick-look modelling pipeline that will allow prediction of mineral formation conditions on timescales that will support rover operations. Our specialized, in detail investigations, in turn, will lead to a unique, in depth understanding of the paleo-environmental conditions and habitability of Gale Crater and Mars' changing environment within the Hesperian.

Joel Davis/Natural History Museum, London
Reconstructing late-stage surface flow events and paleo-environments along Curiosity s ascent of Mt. Sharp, Gale crater, Mars.

The Curiosity rover continues to ascend the foothills of Aeolis Mons (Mount Sharp), Gale crater, Mars, with the objective of characterising habitable environments and reconstructing paleo-environmental conditions. It is widely hypothesized that Mars underwent widespread drying, following the Noachian-Hesperian boundary. However, exactly how quickly the surface environment dried, and whether liquid water continued to be available episodically or regionally, remains unclear. In Gale crater, at the base of Mt Sharp, is the Murray formation, interpreted from investigations by the Curiosity rover as fluvial, deltaic, and lacustrine deposits, which formed in a series of ancient, long-lived crater lakes. Previous orbital observations have suggested that the strata overlying the Murray formation and comprising most of Mount Sharp formed in drier environments, potentially reflecting Mars's changing paleo-climate. However, recent observations by Curiosity have identified strata in the Layered Sulfate-bearing unit (LSu) which may have formed in a sub-aqueous setting, challenging the assumption that the surface environment at Gale (and Mars more widely) dried monotonically.

The overall objective of this project is to investigate how the availability of surface liquid water changed through time in Curiosity's exploration zone and more widely in Gale crater, which is key for understanding how the ancient martian climate changed. It is anticipated that from 2022 onwards, Curiosity will traverse up Gediz Vallis, encountering the Gediz Vallis ridge (GVR), which may record late-stage flow event(s) in Gale crater. Task 1 will use Curiosity's remote sensing instruments to investigate the GVR, establishing whether it partially or wholly comprises fluvially-deposited sediment, whether it represents a single or multiple, pro-longed flow events, and how it relates to the surrounding geology and the canyon that bounds it. Curiosity's predicted traverse will present multiple imaging opportunities for the GVR. Significantly, the GVR may be representative of other late-stage fluvial ridges within Gale crater and elsewhere across Mars.

Surrounding the GVR is the LSu (although their stratigraphic relationships are unclear), which Curiosity is predicted to encounter throughout its future traverse. Task 2 will use Curiosity's near-field and far-field remote sensing instruments to identify and characterize strata within the LSu and into the upper strata of Mount Sharp, which may have formed in a sub-aqueous setting, enabling paleo-environmental reconstructions to be made. Furthermore, high-resolution orbital datasets will be used in parallel to identify analogous strata at similar horizons elsewhere in Gale crater, to determine whether the paleo-environments characterized by Curiosity are reflective of those outside its exploration zone, and evaluate potentially episodic drying cycles. Combined, Tasks 1 and 2 will produce a robust history of late-stage surface flow events in Gale crater, providing critical geological context for understanding its continued habitability.

Both the PI and grad student will provide support to MSL operations, contributing both to day-to-day tactical rover operations and long-term strategic planning.

Lauren Edgar/USGS Flagstaff
Reconstructing Ancient Sedimentary Environments in Gale Crater, Mars: Environmental Evolution and Habitability Assessment

Science objective
The proposed study will acquire and use data from the Mars Science Laboratory (MSL) rover to investigate the sedimentary history and assess the habitability of environments preserved in Gale crater. Orbital and ground-based observations suggest that Gale contains a diverse sedimentary history, and the rover is poised to explore key environmental transitions during the duration of this PS call. The overall objective of the proposed work is to identify sedimentary facies, their spatial distributions and associations, and chronologic relationships in order to reconstruct ancient habitable environments in Gale crater.

Methodology

Task 1 will focus on the identification and description of sedimentary facies and their spatial distributions. This task will use imaging data from Mastcam, MAHLI, ChemCam RMI and the engineering cameras to identify sedimentary facies at various scales based on grain size, sedimentary structures, and composition. The distribution of facies and their associations are a critical part of determining the habitability of ancient sedimentary environments and will provide important context for selecting sample locations.

Task 2 will focus on the construction, correlation, and maintenance of stratigraphic columns. This task will build on Task 1 to determine the relative ages of different geologic units, members, and formations based on stratal geometries. Stratigraphic columns are essential for understanding environmental evolution and chronologic relationships, which will provide further context for studies of chemistry, mineralogy, and the search for organic compounds.

Task 3 will focus on the synthesis of sedimentology, stratigraphy, and geochemical and mineralogical studies, along with reference to analogous terrestrial systems, to reconstruct the paleoenvironmental history in Gale crater. In collaboration with other team members, this task will synthesize results to compile an integrated interpretation of the geologic processes that are recorded in the strata explored by the Curiosity rover. This task will leverage extensive prior experience to develop models for ancient processes and environments in Gale crater using data from Earth analogs as a guide. Synthesis of multiple datasets will be critical to identifying ancient habitable environments and informing drilling and traverse decisions.

Operations

The PI is prepared to actively and regularly participate in daily rover science operations, including serving in at least one operational role. The PI would be interested in participating as a Geology Science Theme Lead, Science Operations Working Group Chair, Long Term Planner, and/or General Science Team member. The PI would be able to advocate for the proposed analyses through these roles and by dialing in to operations on other days on which the PI is not scheduled in a tactical role but could participate as a General Science Team member.

Relevance

The proposed work would directly support the MSL Participating Scientist Program because it addresses the mission objective to to explore and quantitatively assess a local region in Gale crater, Mars, as a potential habitat for life, past or present." Through the identification of sedimentary facies, stratigraphic analyses, comparison to terrestrial analogs, and synthesis and interpretation of paleoenvironments, this work will characterize past habitable environments and place constraints on the duration of aqueous activity in Gale crater. In doing so, the proposed work is also responsive to the goals of deciphering the processes that have formed or modified bedrock and regolith, with emphasis on the role of water" and characterizing major environmental transitions recorded in the geology of the foothills of Mount Sharp."

Christopher Edwards/ Northern Arizona University
From Rover to Orbit: Linking In Situ Thermophysical Observations to Regional Geology and Habitability

Science Goals & Objectives:
The Mars Science Laboratory (MSL) Curiosity rover has encountered diverse sedimentary environments ranging from modern aeolian features to lithified sedimentary units (e.g. mudstones, sandstones, etc.) on its traverse. These sedimentary environments are prevalent around Mars (as seen from orbit and rovers), though discerning the geologic origin and history of these deposits from orbit remains significant challenge. MSL has a unique ability to link high-resolution, rover-scale imagery/composition (e.g. APXS, Mastcam, ChemCam) and thermal infrared data (REMS-GTS) to characterize the diurnal response of geologic terrains with the ultimately characterizing their formation and history. The connections made on the ground can and have been used to link rover-scale to orbital measurements with similar instruments (e.g. THEMIS, CRISM, and HiRISE). The sedimentary units that have been and will be visited by Curiosity are associated with intermediate Thermal Inertias (TI, e.g. 300-650 J K-1 m-2 s-1/2) often associated with cements, lateral/vertical mixing, etc. and are common yet enigmatic across Mars. Ultimately, we will link the geological and depositional history of these intermediate TI units to orbital datasets, ultimately improving our understanding of past depositional conditions across Mars.

Operations:
The PI will participate in operations through 1) Traverse Planning using orbital data to identify hazardous terrains and aid in the identification of unique science targets (e.g. thermophysically/compositionally distinct), 2) Tactical Operations roles like Surface Properties Scientist, and Science Operations Working Group chair, and 3) Science Campaign Advocacy to robustly characterize intermediate TI units (e.g. sulfate-bearing unit).

Methodology:
Three tasks meet science objectives and produce operationally useful data
Task 1. Model TI for all locations with diurnal GTS temperatures. GTS TI context will be examined using Mastcam Clast Survey images augmented with ChemCam RMI. The proportion and size of clasts combined with proportion of regolith in the GTS field of view will be measured to give context to the GTS data. To-date systematic TI derivation has relied on a T and average diurnal temperature approach. Here we modify this through complex surface models that fit the full diurnal curve.
Task 2. Use GTS to develop complex surface models. Diurnal temperatures are sensitive to small differences in the physical nature of the surface. By leveraging diurnal GTS data, it is possible to uniquely separate the behavior of different surface components. These results will be tied to MSL datasets (e.g., Mastcam, ChemCam, APXS, etc.) to

differentiate intermediate TI units in Mt. Sharp. For example, we aim to differentiate fine-scale layering, surface heterogeneity, and pore-filling cements, especially for to be explored units such as the Mg sulfate-bearing unit.
Task 3. Use multi-time of day orbital data to classify GTS TI in broader context. Ground truthing of multi time-of-day THEMIS orbital data at key locations (e.g. sulfate unit, Murray, VRR) will help make testable predictions about the future landscapes and other similar locations (central crater mounds) across the surface of Mars. For example, having the same bulk TI, loess stones and true sandstones will have significant differences in pore-filling cements which can be unraveled through our approach.

Relevance:
The proposed work is relevant to the MSL project and directly addresses multiple science objectives including: 1) Characterization of geological features contributing to deciphering geological history and the processes that have formed or modified bedrock and regolith, with emphasis on the role of water, and 2) Exploration and characterization of major environmental transitions recorded in the geology of the foothills of Mount Sharp and adjacent plains.

Jennifer Eigenbrode/NASA Goddard Space Flight Center
Science PI: James Lewis
Investigating the Preservation Potential of Organic Matter in Sulfate-Rich Strata in Gale Crater

The goal of this proposal is to better understand how diagenesis may have influenced organic matter preservation in sulfate-rich deposits formed in different Martian environments. This will be achieved through laboratory experiments that replicate these geochemical conditions in the presence of different organic materials. The proposed work is motivated by the fact that the Curiosity rover is currently traversing a transitional region between clay-bearing and sulfate-bearing strata that is suspected to represent a major environmental change in the history of Gale crater. Investigating the organic chemistry of this region and the overlying sulfate-bearing unit (SBU) is an essential component of fulfilling the rover's goal to examine how the habitability of Gale crater has changed through time. Images of the transitional and SBU strata suggest diagenetic features overprinting the original rock fabric. The proposed laboratory investigations will examine (1) what organic species may have survived such diagenetic processing, (2) the organic residues from organic compounds susceptible to alteration, and (3) the sulfate-rich units most amenable to organic matter preservation. These data will enhance our understanding of such environments as Curiosity enters this new phase of the mission and workspaces dominated by diagenetic features and sulfates.

The proposed laboratory work focuses on the aqueous alteration of sulfate-organic mixtures via reactions in a Parr pressure vessel inside an oven. The highest reaction temperatures will be capped at 225ºC, as this was the likely upper limit for diagenetic processes in Gale crater as found by Borlina et al. (2015). The starting mixtures will explore the range of potential depositional and diagenetic environments that formed the clay-sulfate transition and the SBU (i.e., aqueous versus eolian deposition, different mixing ratios, temperatures, or water-rock ratios). The work will focus on the impact of magnesium, iron, and calcium sulfates as these are the sulfate species that are likely most common in Gale crater. The organic materials will represent different classes of meteoritic, geological, and biological organic matter that may have been present on ancient Mars (such as carboxylic acids, carboxylates, amino acids, and macromolecules). Oxalates, acetates, and benzenecarboxylates will represent the likely products of the radiolytic and oxidative breakdown of organic matter. Fatty acids, fulvic acids, and amino acids will be utilized as they are compounds of high priority for astrobiological investigations. A Type IV kerogen will be used to represent macromolecular carbon. These materials and methods will enable a large range of samples to be generated and for discoveries by the rover to be rapidly responded to. The samples will also be made available to the wider MSL team.

The samples will be assessed by a suite of laboratory techniques. X-ray diffraction (XRD) will be used to characterize the crystalline components. Evolved gas analysis mass spectrometry will provide insight into the organic compounds present and the minerals with which they are associated. Gas chromatography mass spectrometry of solvent and thermal extracts will provide an inventory of the organic compounds present in each sample. Fourier transform infrared spectroscopy will be used to examine sample mineralogy and the organic species present on mineral surfaces. The laboratories in which this work will be conducted are also equipped to perform analyses analogous to those conducted by the Sample Analysis at Mars (SAM) instrument suite and Chemistry and Mineralogy (CheMin) XRD instrument on board Curiosity. This will enable high fidelity comparisons between our laboratory data and flight data.

MSL Operations will be supported through training as a Geology Keeper of the Plan (GEOKOP) and a continuation of work as Payload Downlink Lead (PDL) for the SAM instrument suite.

William Farrand/Space Science Institute
Examining alteration environments of granular basaltic materials using combined results from APXS, ChemCam, and MastCam compared against terrestrial analog datasets

Sample Analogs

Rocks examined by the Mars Science Laboratory rover Curiosity have been dominated by forms of clastic rocks broadly of basaltic composition. While clastic sedimentary rocks are ubiquitous on Earth, clastic rocks of basaltic composition form a relatively minor fraction of the terrestrial geologic record. Multiple studies by a variety of researchers, including the proposed PS, have been carried out on terrestrial analog datasets of granular volcanic materials formed in a variety of environments. These types of materials range from pyroclastic deposits later affected by ambient alteration, hydrovolcanic ashes deposited with steam, and mechanically eroded and fluvially deposited basaltic granules. Especially relevant to the on-going and future studies by Curiosity are those studies where the granular basaltic materials were deposited with, or later affected by, sulfur-bearing gases or fluids to produce secondary sulfate minerals. Results from such studies that are publicly available, including one associated with the proposed PS, will be used as a source of comparison against data that has been, and will be, collected by Curiosity in order to determine the environmental factors that existed and that produced the rocks currently extant in Gale Crater. Also of relevance for comparison against collected and to-be-collected data from Curiosity are data from the Mars Exploration Rovers Spirit and Opportunity since both sampled pristine granular basaltic materials as well as those altered to sulfates.

MSL Datasets and Processing Approaches

The proposed PS would use multispectral data from Mastcam, passive reflectance data from ChemCam, as well as chemical information derived from both APXS and ChemCam to search for patterns in common with the terrestrial analog datasets and data from the Spirit and Opportunity rovers. The Mastcam multispectral and ChemCam passive hyperspectral data are largely underutilized datasets. Spectra of regions of interest from Mastcam multispectral data and ChemCam passive reflectance spectra will be examined as-is and will be reduced to sets of spectral parameters. Library spectra of the terrestrial datasets would be similarly parameterized. The proposed PS would apply advanced multi- and hyperspectral endmember determination and spectral matching approaches to help identify the mineralogical constituents in the archival data from Curiosity as well as to current data being collected. In addition to the spectral matching techniques, a set of machine learning classification routines will be applied to the data. These classification techniques require training against existing data and both the terrestrial analog, Spirit and Opportunity data, and data collected to-date by Curiosity will be used as training sets. The machine learning classification approaches are also very effective with geochemical data and would also be used with the chemical information from APXS and ChemCam to the extent that they are not duplicative of past efforts.

Relevance

This proposed investigation is relevant to the MSL Participating Scientist Program in that it addresses two types of investigations specifically called for in the Announcement of Opportunity, first, Investigations are sought of the evolution of igneous protoliths indicated by sedimentary rocks and their alteration pathways" and to the extent that the terrestrial analog datasets to be used include diagenetic alteration it also addresses the desired investigation to leverage Earth field and sample analysis experience in studies of sediment diagenesis". It is also relevant as an investigation addressing the MSL science goal and desired investigation for the Determination of the mineralogy and chemical composition & of surface and near surface materials".

Heather Franz/NASA Goddard Space Flight Center

Deciphering Gale Crater s Sedimentary and Environmental History through Stable Isotopes

Study of Mars' volatile inventory is vital for understanding the planet's geological processes and evolution, as well as the potential for past or present habitability. The Sample Analysis at Mars (SAM) instrument on the Mars Science Laboratory (MSL) Curiosity rover is uniquely equipped to perform experiments designed to study martian volatiles and habitability. Analysis of stable isotope ratios is a key method by which SAM approaches this problem. The combined capabilities of its Quadrupole Mass Spectrometer (QMS) and Tunable Laser Spectrometer (TLS) allow SAM to measure isotopes of C, O, H, S, and Cl released as CO2, CH4, H2O, SO2, and HCl. The proposed work will optimize the scientific return afforded by isotopic investigations pertinent to the past and present martian climate, including a dramatic shift in global surface environment that may have occurred during Mars' late Noachian period. This environmental shift may be recorded within a transition zone from phyllosilicate-rich to sulfate-rich sediments within the foothills of Mount Sharp, which Curiosity is poised to investigate in the immediate future. The Participating Scientist (PS) will also determine isotopic compositions of volatile compounds that carry clues concerning sources for sediments within the crater.

As Curiosity has progressed from its landing site near Yellowknife Bay to its current location at the transition zone, SAM has been characterizing the stable isotopic composition of volatiles released through thermal processing of mudstone, sandstone, and aeolian deposits. Previous analyses along the traverse have yielded a wide range of isotopic compositions among mineral phases in various samples. Similar variations in isotopic compositions on Earth often indicate biological processing, reflecting a key motivation for studying stable isotopes on Mars. Continued analyses of isotope ratios in volatile compounds as Curiosity climbs through the sulfate-rich layers of Mount Sharp will be crucial for comparing sediment sources for the sulfate unit versus those below, as well as for constraining relative alteration histories of the units. The PS will contribute to this effort by (1) advocating for SAM analyses of samples likely to inform interpretations of Gale crater's sedimentary and environmental history, (2) refining the QMS capability to retrieve isotopic data through improvements to instrument calibration and removal of artefacts, and (3) calculating isotope ratios for C, O, H, S, and Cl and abundances of various evolved gases from QMS data. In addition, the PS will characterize the current martian climate through assessment of seasonal and interannual variations in the isotopic composition of atmospheric CO2 and water. Observations to date indicate larger variations than expected based on laboratory models, suggesting incomplete understanding of the global-scale system. The PS will provide input regarding the optimal sampling strategy with SAM to further investigate seasonal trends in isotopic composition. Trends suggested by existing data hold potential implications concerning martian surface and sub-surface volatile reservoirs.

This work is relevant to the following MSL science objectives: (1) determination of the stable isotopic and noble gas composition of the present-day atmosphere and of ancient

H_2O and CO_2 preserved in hydrated minerals; (2) identification of potential biosignatures (chemical, textural, isotopic) in rocks and regolith; (3) characterization of the local environment, including basic meteorology, the state and cycling of water and CO_2, and the near-surface distribution of hydrogen; and (4) exploration and characterization of major environmental transitions recorded in the geology of the foothills of Mount Sharp and adjacent plains.

Scott Guzewich/NASA Goddard Space Flight Center
Devils on Mt. Sharp: Dust Lifting in Gale Crater

Science Goals: Martian dust is predominantly lifted into the atmosphere through two processes, both of which are believed to supply roughly half of the atmospheric dust load: dust devils and surface wind stress leading to saltation and suspension. While the latter is seasonally and regionally variable in occurrence, dust devils are relatively ubiquitous across the planet. Yet, despite the incredible importance of both processes to the atmosphere and modern climate, neither is well measured from the surface in situ. While Gale Crater was initially believed to be relatively devoid of dust devils [17] the change in rover location higher on Mt. Sharp and changing directions of dust devil imaging has shown an abundance of activity along and adjacent to Curiosity's path [e.g., 2]. We propose to create new dust devil movies for Curiosity to quantify the dust devil activity record in Gale Crater. We will employ the Navigation Cameras (Navcam), Mast Camera (Mastcam), and the Rover Environmental Monitoring Station (REMS) to answer three science questions:

1. What is the spatial distribution and frequency of observed Gale Crater dust devils?
2. What are the observed meteorological characteristics of dust devils near enough to the rover to be detected by the Rover Environmental Monitoring Station?
3. How much dust do dust devils in Gale Crater lift into the air?

Direct measurements of dust lifting are a high priority of the Mars Exploration Program Analysis Group and our work would contribute to addressing these fundamental unknowns about martian climate processes.

Methodology: We will utilize Navcam, Mastcam, and REMS observations to measure dust devil frequency, location variability, and dust lifting efficiency in Gale Crater. We will work with the Navcam and Mastcam instrument teams to create new dust devil movies and optimize their cadences to best capture the processes related to dust lifting and dust devils in Gale Crater. This is particularly timely for Extended Mission 4 (EM4) as dust devil activity is expected to increase as Curiosity transits the sulfate unit of Mt. Sharp [2].

Relevance to the MSL Participating Scientist Program: We propose to create new MSL instrument sequences with Navcam and Mastcam to address our three Science Questions and understand how dust devils lift dust in Gale Crater. We will be engaged in operations to make tactical decisions in the use of these new movies (e.g., pointing angles and timing) so they are best used to address our Science Questions. Our proposed work uses MSL instrument data to address mission science objectives. Specifically, we will use Navcam, Mastcam, and REMS observations for Characterization of the local environment, including basic meteorology." Dust lifting processes and dust devils are poorly characterized in situ on the martian surface and our work would help resolve this deficiency through the longest existing record of dust devils observed from the surface. Dust lifting represents one of the few truly stochastic processes in the modern martian climate that drives weather and variability and understanding it is vital for understanding the modern climate and working toward future martian weather prediction. This work addresses key Mars Exploration Program Analysis Group science goals related to the modern climate. Additionally, we will support MSL operational planning in up to three roles, as required by the solicitation, and provide leadership in the strategies for meteorological investigations using REMS, Mastcam, Navcam, and/or ChemCam as well as rapid data analysis to inform ongoing operations."

Craig Hardgrove/Arizona State University
Investigations of Hydration, Geochemistry and Stratigraphy Using Neutron Measurements from the Dynamic Albedo of Neutrons Instrument on the Mars Science Laboratory Curiosity Rover

Our proposed research has three primary objectives:
(1) To participate in Mars Science Laboratory (MSL) Curiosity rover operations and provide tactical science results from the Dynamic Albedo of Neutrons (DAN) instrument to the wider MSL science team. We will develop a new method for rapid reduction of DAN active data to derive abundances and distributions of hydrogen (H) and neutron absorbing elements with depth.
(2) To use DAN data to determine the in-situ hydration of clay-rich and/or sulfate-rich materials with depth in the Mg-sulfate unit and throughout Gedis Vallis.
(3) To understand how DAN passive and active data may be used to investigate the hydration of nearby topographic features.

DAN data have been used to characterize the hydration of basaltic dune materials, to constrain the distribution of hydrated amorphous phases, to identify the presence of a buried high-silica volcano-sedimentary layer at Marias Pass, and to identify the depth distribution of hydrated high-silica fracture halos. DAN continues to provide important context to ongoing investigations of clays and alteration features around the hematite- and clay-bearing outcrops. DAN provides a unique view into the Martian subsurface that extends to depths of one meter and has now collected thousands of neutron spectra across a variety of compositions and subsurface features. DAN will continue to provide critical insights into the distribution of hydrated materials, Mg-sulfates and evaporitic materials throughout the next phase of Curiosity's mission. We propose 1) a new method of retrieving subsurface parameters from DAN measurements that will enable the MSL science team to tactically review DAN results and plan future DAN measurements; 2) to participate in rover operations to help plan new DAN observations; and 3) to work with the MSL science team to plan DAN measurements that ensure the DAN data are representative of the drill/study sites and can be used to improve SNR. We will also plan complementary data to be collected at each site that will give future researchers the ability to test hypotheses about subsurface hydration. This will require consideration of the local geology and elemental chemistry, as well as participation in the planning of the rover to ensure the DAN sensing area is positioned over a suitable location. Eventually, the DAN PNG will no longer function or will produce so few neutrons that active measurements require substantial rover resources. DAN passive data will then be used as a guide to help the MSL science team identify locations that may have increased hydration in the subsurface. Lastly, we propose to use DAN passive measurements in new ways that leverage the changing terrain as Curiosity traverses up Mount Sharp to determine the sensitivity of DAN to materials around the rover exposed in cliff faces or walls. This work supports the goals of the MSL PSP program by helping to determine & the mineralogy and chemical composition (including an inventory of elements such as ... H) of surface and near surface materials", as well as & determination of ... ancient H2O ... preserved in hydrated minerals."

Elisabeth Hausrath/University Of Nevada, Las Vegas
Examining chemical and mineralogical alteration in Gale crater for evidence of past habitability, biosignature preservation potential, and potential biosignatures

Liquid water is essential to all known life, and its characteristics are also critical to biosignature preservation and the formation of potential chemical biosignatures. Here we propose to examine chemical and mineralogical evidence of alteration in Gale crater to help understand geological features contributing to deciphering geological history and the processes that have formed or modified bedrock and regolith, with emphasis on the role of water" using the three tasks described below.

In Task 1, we will analyze geochemical, mineralogical, and image data to identify samples as more aqueously altered versus less aqueously altered. Signatures of past aqueous conditions can be preserved in both the mineralogy and chemistry of the altered material, and we will therefore use mineralogical data from CheMin, chemical data from ChemCam and APXS, as well as images from the Mars Science Laboratory Curiosity's Engineering and Science cameras.

In Task 2, we will perform both thermodynamic and reactive transport modeling supported by laboratory experiments to interpret the observations from Task 1. This modeling will allow a quantitative interpretation of past aqueous conditions including pH, water: rock ratio, duration of aqueous alteration, solution composition, temperature, and oxidation state, and will be performed on a timeline to assist in both operations and the general mission science observation. Laboratory experiments will focus on quantifying water-rock interactions for Mars-relevant minerals to support the modeling. These activities proposed in Task 2 specifically respond to the call for investigations that leverage expertise in aqueous geochemistry to constrain fluid conditions through time at Gale crater based on elemental abundances and mineral assemblages measured in Mount Sharp's rock record."

In Task 3, we will examine elemental concentrations, particularly trace elements, for potential chemical biosignatures addressing the goal Identification of potential biosignatures (chemical, textural, isotopic) in rocks and regolith". We will specifically look for three different ways chemical biosignatures can be formed, including (1) the impact of biologically generated organic compounds on trace elements, (2) the formation of precipitates associated with microorganisms, and (3) preservations of trace elements in microorganisms within minerals. For (1), previous work has shown that leaching by organic compounds preferentially removes trace metals based on the complexation constant of the organic compound with the element. Such organic leaching has been shown to preserve evidence of early life on Earth, and may also preserve evidence of early life on Mars. ChemCam data will therefore be examined addressing the call for investigations that leverage expertise with chemical biosignatures and trace element indicators of environmental conditions using ChemCam LIBS data.". For (2), past work has shown that microorganisms can preferentially precipitate metals. In this case, ChemCam data will be examined for metals associated with biological components known to be associated with life such as C, H, N, O, P, and S. Finally, for (3) previous work has shown that microorganisms can be preserved in phases such as clay minerals and chert, and the elements present within the microbial metallome" can be preserved as a trace metal signature of past life. The trace element composition present in minerals such as clay minerals, chert, and others will therefore be examined for evidence of past life. We have previously performed work examining all of these types of potential chemical biosignatures.

The PI will fully discharge the responsibilities of being a Mars Science Laboratory Participating Scientist, including regularly contributing to daily rover operations and serving in at least one operational role.

Jeffrey Johnson/Johns Hopkins University
Compositional and Photometric Studies along the MSL Traverse

We propose two major tasks involving (1) the use of ChemCam as a passive reflectance spectrometer to acquire visible/near-infrared (400-840 nm) spectra for compositional and mineralogical studies, and (2) spectrophotometric observations of surface scattering properties using Mastcam and MAHLI. As previously shown by [108] the ChemCam spectrometers can be used in passive mode (no laser) to collect relative reflectance spectra (400-840 nm). Such spectra have been used to constrain the mineralogy of rocks, soils, and sands bearing ferric oxides, ferric sulfates, and hematite ([108], [112], [66], [91], [95]) as well as pyroxene and olivine ([113], [115]). Published multispectral observations made by Mastcam at multiple times of day along the rover traverse provided information on the relative wavelength-dependent light scattering properties among pristine and disturbed rocks and soils ([105], [107], [109], [111], [114], [120], [121]). MAHLI has been used as a goniometer at a single time of day to provide photometric data sets of targets within the arm work area ([144], [107], [111]).

The PI will work with the ChemCam team and Science Theme Group (STG) to develop, advocate, and acquire passive spectroscopy observations/activities of targets of interest and provide near real-time analyses of the data. Available software will be used to convert ChemCam measurements to units of radiance and to calculate ratios between a surface target observation and that of the ChemCam calibration target (acquired at the same exposure time). The resultant relative reflectance spectra will be interpreted to constrain iron mineralogy of surface targets, in combination with other MSL instruments [108]. The PI will also work with the Mastcam team, STG, and rover planners to develop multiple time-of-sol photometric imaging sequences. For Mastcam we will use the M-34 camera at four wavelengths, accompanied by Navcam stereo images to provide geometric information to calculate local surface facets. Multi-band Photometry QUBs" will be created that contain radiometric and geometric information for all scenes acquired. These can be used to enable radiative transfer (Hapke) modeling of atmospherically-corrected data of different geologic targets to quantify variations in scattering properties as a function of wavelength ([100], [109], [122], [121]). Photometric observations of materials within the arm work area will be acquired by using MAHLI as a goniometer, where images will be acquired at 20 arm positions at a single time of sol, all centered at the same location within the work area, and all from a near-constant distance from the surface (e.g., 100 cm). Such data sets also provide sufficient views around a target to enable the construction of detailed, three-dimensional views of surface materials for use in topographic modeling and geomorphologic studies, as well as photometric models using radiance data from the MAHLI images [144].

The PI will participate in daily operations, team meetings, and prepare archives of data products generated by this investigation for the PDS. The PI will serve as Science Theme Lead for the Geology/Mineralogy group and as a SOWG Chair. The PI will work extensively with other team members to provide passive ChemCam and Mastcam spectral products and interpretations useful to their investigations. The PI will report on results at Science Discussion, professional conferences, annual reports to NASA, and in peer-reviewed publications, and support education and public outreach efforts.

The proposed work is relevant to the MSL mission because it addresses the mission science objectives to: (1) characterize geological features to help decipher the geologic processes during evolution of the surface; (2) determine the mineralogy and chemical composition of the surface/near-surface; and (3) explore and characterize the major environmental transitions recorded in the geology of the foothills of Mt. Sharp and adjacent plains.

Edwin Kite/University of Chicago
Linking rover observations with models of timing and flow of surface and subsurface waters at Gale crater

Mars Science Laboratory (MSL) has confirmed that Gale was once a habitable environment, with flowing water. However, basic unknowns remain, and the Announcement of Opportunity (AO) for this PSP prioritize[s] through this program element [investigations] that leverage expertise in hydrology to link rover observations with models of timing and flow of surface and subsurface waters at Gale crater." Motivated by the potential of MSL's traverse through the sulfate-bearing units to improve understanding of surface and subsurface water flow (and thus past habitability) at Gale, the broad goals of the proposed investigation are to constrain the burial and groundwater history (taphonomic path) of the sulfate-bearing units; determine water flow paths; and determine whether the paleoclimate recorded by the sulphate-bearing units was frigid or alternatively warmer (with an Earthlike hydrologic cycle). The sulfate-bearing units contain abundant deformation features and concretions that record past subsurface fluid flow and burial conditions, and the sulfate-bearing units are a decisive location for testing models of Mount Sharp's surface water source and paleoenvironment [1]. Additionally, understanding burial conditions and fluid flow is critical for identifying areas where paleoclimate signatures and potential biosignatures are most likely to be preserved. Therefore, making the best use of this opportunity to improve understanding of fluid flow (and thus habitability) at Mount Sharp requires an investigation that is tied to operations directly as it will provide context (as the team decide what to target) that cannot be provided using existing MSL and remote sensing data. The relevant MSL mission-level science objectives, the objectives of the proposed investigation, the tasks to be performed, and the relationships between tasks and objectives, are shown in Table 1.

Objectives are as follows:
Objective 1 (§2.4.1): Use observations of fractures, veins, and deformation features to distinguish between hypotheses for the flow paths and peak pressures of subsurface fluid flow at Mount Sharp.
Objective 2 (§2.4.2): Determine whether the sulfate-bearing unit formed in a paleo-low or as a paleo-high, using paleoflow direction indicators, analysis of large-scale unconformities, and ground truth of candidate layer sequences mapped from orbit in the sulfate-bearing unit.

Alongside service in daily operational roles, and participation in one or more Science Theme Groups, mission operations will be enhanced by rapid-turnaround modeling to provide context for target selection. This includes synthesis and integration with modeling of past groundwater flow, and models of past warm states that produced liquid water (among other models), all updated in response to site-by-site data collection. These models, which run in seconds-to-hours, and which also enhance the proposed science investigation, are described in grey boxes in this proposal. The proposal is directly responsive to topics specifically called out in the AO as well as to MSL objectives, e.g. "Characterization of geological features contributing to deciphering geological history and the processes that have formed or modified bedrock and regolith, with emphasis on the role of water" and "Exploration and characterization of major environmental transitions recorded in [&] Mount Sharp" (Table 1). The proposed investigation requires integration with the MSL team, and therefore it is relevant to this PSP and is not relevant to MDAP. Two graduate students, who are identified in the Expertise and Resources Appendix, will gain experience through participation in this investigation.

Kevin Lewis/Johns Hopkins University
Probing the Subsurface at Mount Sharp: Quantitative Stratigraphy and Gravimetry

Objectives: The objective of the proposed work is to understand the deposition and diagenesis of Mount Sharp through physical properties of its stratigraphy. To do this, we propose two parallel investigations that probe the stratigraphy beyond what is exposed at the surface.

First, we propose to use stereo imaging to constrain the 3D orientation of layering along the rover traverse. This allows us to create a geometrically accurate stratigraphic column, as well as to relate disparate outcrops with uncertain stratigraphic relationships. This is important where bedrock exposures are discontinuous, as commonly occurs at Mount Sharp. Previous work has shown that the layers of Mount Sharp deviate from horizontal by several degrees, such that rover elevation alone cannot be used as a proxy for stratigraphic position [e.g., 14]. This analysis has consequences for the interpretation of other rover data sets, including Chemcam, APXS, and drill targets, as the relative stratigraphic positions of individual targets can become reordered after ap- plying a corrected dip to the rocks. We will make the updated positions available to the team on an ongoing basis. We have developed techniques to use both single-position as well as long-baseline stereo imaging (from two rover positions) to extract the 3D geometry of exposed layering. Further, as the rover moves into the potentially cross-bedded Gediz Vallis and Mg-sulfate-bearing rocks higher on Mount Sharp, stereo reconstruction will allow us to determine paleoenvironmental variables such as transport directions from bedform orientation. These measurements help us to span the gap from the grain scale to the outcrop scale, grounded in terrestrial field experience.

The second portion of the investigation uses of the Rover Inertial Measurement Unit (RIMU) to continue the first surface gravity on Mars, following an initial study by [32]. That study calibrated the engineering accelerometers within the RIMU to measure surface gravitational acceleration along the rover traverse, from which the bulk density of the rocks at Mt. Sharp could be determined. Extending this traverse as the rover continues to climb Mt. Sharp will allow us to 1) reduce uncertainty on the bulk density measurement published by [32]; 2) look for density variability within the stratigraphy, particularly across the transition to the sulfate-rich unit; 3) deconvolve potential signals arising from the deeper structure of Gale crater itself, as discussed by [24]. This work is highly complementary to the nominal capabilities of Curiosity's science payload. Major implications of these gravity measurements include the permeability of Mount Sharp rocks to subsurface fluids as well as the burial and compaction history of the mound - both of which are essential to understanding the origin and evolution of the sedimentary units. No additional work is required from the MSL engineering team to obtain or interpret these data. This proposal will also publicly archive these data with the PDS.

Methodology: The proposed work will make use primarily of Mastcam and Navcam stereo image data and derived terrain models, from which bedding attitudes can be calculated. We will use improved data extraction and regression techniques that will build upon previous rover-based studies. Analysis of gravity data from the RIMU will build upon the techniques described by [32] and [24].

Relevance: The proposed work is relevant to several top-level goals of the MSL mission, including characterization of geological features contributing to deciphering geological history and...processes" and characterization of major environmental transitions recorded in the geology...of Mount Sharp", as well as several of the specific investigations of interest sought by MSL Participating Scientist Program, as described in more detail within the proposal.

Lucy Lim/NASA Goddard Space Flight Center
Geochemistry and paleoenvironments in the Gale Crater clay/sulfate and sulfate-bearing regions

A coordinated study is proposed of compositional data from APXS, ChemCam, and other MSL instruments as available (CheMin for mineral identifications; SAM dehydroxylation data when available; MAHLI and MastCam for essential context) to understand the clay/sulfate transition in Gale Crater. Recent studies (for example Sheppard et al. 2021, Rapin et al. 2021) based on CRISM spectroscopy and ChemCam remote imaging data have suggested that the layered sulfate bearing unit is mixed with clays and mudstones throughout, likely indicating variability in the Martian paleoclimates. In situ data from the rover's future traverse will provide currently-unknown information on the physical scales of the clay/sulfate mixing and further evidence on the nature and timing of the diagenetic processes involved. Analysis and modeling of the elemental abundance data from APXS and ChemCam will be essential to understanding the chemistry of the mixed clay and sulfate units and to selecting drill sites for CheMin and SAM analysis.

Additionally, the PI will regularly support rover operations including tactical operations planning shifts, participation in the Geology and Mineralogy science theme group, and all required training for operational roles as needed. Compositional information from ChemCam and APXS will be evaluated on a tactical timeframe to inform the selection of future drilling and other science targets.

The proposed effort directly addresses the MSL science objectives, "Determination of the mineralogy and chemical composition of surface and near surface materials," "Exploration and characterization of major environmental transitions recorded in the geology of the foothills of Mount Sharp and adjacent plains," and "Characterization of geological features contributing to deciphering geological history and the processes that have formed or modified bedrock and regolith, with emphasis on the role of water."

Majd Mayyasi/Boston University
Using MSL to Assess Surface-to-Space Atmospheric Variability and Effects on Habitability

The motivation for this project is to investigate the attenuative properties of the martian atmosphere and ionosphere in response to solar irradiance, solar energetic particles, and to radio waves used to communicate with the rover. The investigation on irradiance attenuation will identify presently uncharacterized metal species in the atmosphere. The investigation on solar energetic particles will provide empirical atmospheric attenuation parameters. The investigation on radio wave attenuation will result in a proof-of-concept of a novel approach to determining atmospheric properties from routine rover-to-orbiter relay. These investigations collectively will yield data essential to the determinations of the shielding capacity of atmospheric neutrals and plasma as a function of local time and martian season. The results of this work could then inform recommendations on optimal habitability conditions at Mars.

The specific science questions to address in this proposal are:
1) What is the abundance of specific metal species in the martian atmosphere?
2) What is the total electron content above MSL?
3) How effectively does the martian atmosphere attenuate solar and radio sources?

NASA PDS data will used for the investigation of solar source attenuation using measurements from the Mars Science Lab (MSL) and the Mars Atmosphere and Volatile Evolution (MAVEN) missions. The data sets from these two missions will be used with a numerical model to address the first and third science questions.

The second science question will be addressed using a new approach to analyze ancillary (telecom) data used by MSL to relay with orbiters. The relay radio signal attenuates in a way that describes the total column of electrons in the intervening ionosphere between the rover and relay orbiter. This measurement technique has never been attempted at Mars, and will reveal the full electron content in regions that no other spacecraft or measurement technique can reliably probe.

The results from the investigations will yield: the first empirical constraints of Na, K, and Mg metal species in the atmosphere of Mars; a new capability to measure and characterize the ionosphere from the vantage of a surface asset at Mars; and, empirically-derived absorption cross-sections for solar energetic particles. The analysis includes quantifying the spatial, diurnal, and seasonal variability of the attenuative capacity of Mars' environment in the present epoch. The results from this work will inform the community of the shielding capacity of the martian atmosphere as a function of local time and martian season for recommendations on optimal habitability conditions, and surface communication strategies.

John Moores/York University
Investigating Variability in Ice, Dust and Methane at Gale Crater

I. Science Goals and Objectives

MSL has completed several Martian years of observations that provide a baseline for this proposal. We propose to further these successful observational campaigns while addressing novel questions raised by the mission, building on these results to better understand the unique atmosphere of Gale Crater:

A. Characterize the inter-annual variability of different populations of thin water ice clouds
Thin clouds are often visible in NavCam perturbation images. However, clouds occurring at different times of the day and at different points in the year may form distinct populations made up of different kinds of particles at different altitudes. Each will provide distinct insights on water transport and processes occurring at different altitudes.

B. Characterize the changing nature of airborne dust and its flux throughout Gale Crater
NavCam, MastCam and ChemCam have identified the seasonal cycle in dust loading, lifting, deposition and dust size at a single pointing in Northern Gale. Extending these techniques to the entire crater visible to MSL will address transport of dust while shape information will refine models of the transfer of solar and thermal radiation in the Martian atmosphere.

C. Link transport to dust settling, Rhythmite formation and the potential to preserve organics on Amazonian Mars.
Constraints on dust transport will allow locations with net deposition to be identified and for that deposition to be quantified and compared to Rhythmite formation in the present era. Combining the settling rate with an UV Radiative Transfer (UV-RT) Code will determine if the rate of burial is sufficient to preserve organic carbon compounds, precursors to methane production, in these formations.

D. Constrain the Methane diurnal cycle and plume dynamics
MSL's SAM-TLS instrument has observed methane in the Martian atmosphere with seasonal and diurnal variations in concentration as well as periodic spikes. Addressing the timing and persistence of methane in the atmosphere will help constrain the quantity of emission and will provide key data for modelers to trace these emissions back to their source.

II. Methodology

Objective A will use zenith NavCam movies to obtain cloud feature size, direction, and translation rate. Sky surveys will determine the scattering phase function of these clouds, providing cloud particle shape. Cloud altitude may be derived from shadows of clouds tracked against Aeolis Mons.

Objectives B and C will use NavCam and MastCam imagery of the crater rim and a 3D RT code [37][38] to determine extinction as a function of height and position on the crater rim. A 1-D Planetary Boundary Layer model will quantify dust settling and a UV-RT code [13] will determine potential for exogenous organic burial. ChemCam passive spectroscopy scans near sunset will probe the forward scattering lobes of the dust phase function to provide information on particle shape and packing.

Objective D will build up detail on the diurnal cycle of methane to address whether it is likely the product of generalized seepage (as in Objective C) or whether enhancements are associated with specific times, suggesting distinct source regions. Enrichment measurements will be executed in sets of 3 over 30 hours to provide the first exploration of plume dynamics from buildup through peak and onto decay phases.

III. Relevance

This proposal is relevant to MSL science objectives detailed in MSLPS Program page C.28-3, bullet 8 "Characterization of the local environment..." This proposal also addresses the prioritized investigations, bullets 5 ("…leadership in the strategies for meteorological investigations using REMS, Mastcam, Navcam and/or ChemCam…") and 6 ("…enhance the science return from SAM measurements of organics through innovative operational approaches … with a focus on mineral/organic interactions, radiation transformation of organics…").

Sharon Purdy/Smithsonian Institution
Unraveling the Late Geologic History and Associated Habitable Environments in Gale Crater

The Mars Science Laboratory (MSL) Curiosity rover is exploring the surface of Mars with the goal of assessing the potential for past or present life in Gale crater. This proposal contributes to the MSL Science Objective to characterize the geological processes and geologic history, with emphasis on the role of water in forming and (or) modifying the bedrock. The proposed research will enhance and broaden the scientific return of the mission and will directly support the Science Operations of the rover by identifying and promoting scientifically interesting targets for investigation by the MSL Rover.

The goal of the proposed research is to characterize the hydrologic and climatic environment associated with the formation of young" aqueous landforms along the future MSL traverse: the Greenheugh pediment, Gediz Vallis, Gediz Vallis ridge, and associated deposits. These deposits post-date the formation and subsequent erosion of the of the clay-and sulfate-bearing units and are significant as the results from the proposed analyses will provide unique insight into the geologic history that records the latest potentially habitable environments in Gale. The proposed research will link rover observations to hydrologic models to quantify the amount of surface water that permitted their formation. This proposed research addresses the following science objectives: 1) Characterize the sedimentological properties of the outcrops, 2) Estimate the magnitude, source, and frequency of the formative flows responsible for the deposits to assess their geologic significance and associated paleohydrology, and 3) Create supporting documents (e.g., stratigraphic columns) that provide visual representation of the outcrops, and use rover observations to ground truth" high-resolution orbital data.

The proposed work will utilize images from the MSL Mast Camera (Mastcam) and Mars Hand Lens Imager (MAHLI), and Chemistry and Camera (ChemCam) Remote Micro-Imager (RMI). Mapping at an outcrop scale will help define the units and rock types based on the physical characteristics. Clast size and shape will be determined using image software and the distribution of grain sizes will be determined for each sample. Hydraulic calculations will be used to estimate velocity, discharge, and flow depth based on the grain size distributions. The sedimentologic characteristics will be used to constrain the formative transport processes and provide insight into the associated paleoenvironment. The extent, boundaries, and elevation of units and facies mapped from orbit using HiRISE data based on color, textural variations, and elevation (100 m contours) will be refined and extrapolated laterally as outcrops are characterized. The results of the analyses will be incorporated into supporting documents and geologic maps created in ArcGIS that correlate rover and orbital observations.

The proposed research and results directly address the MSL science objectives (C.28-3 of the MSL Participating Scientist Program (PSP) call) including 1) Characterization of geological features contributing to deciphering geological history and the processes that have formed or modified bedrock and regolith, with emphasis on the role of water," and 2) Exploration and characterization of major environmental transitions recorded in the geology of the foothills of Mount Sharp and adjacent plains." This proposed research directly addresses the listed prioritized investigations sought through this program element (C.28-4 of the MSL PSP call).

Deanne Rogers/State University of New York, Stony Brook
Constraints on the formation and diagenetic history of Gale crater strata from physical properties

The bulk physical properties (grain size, porosity, density) of rocks are strongly influenced by depositional process, burial depth, and alteration. Therefore, constraints on physical properties are important for interpreting the depositional and diagenetic history of strata within the floor and central mound of Gale crater. The formation and diagenetic history of strata, in turn, are key to assessing the duration and characteristics of habitable conditions and the fate of any biogenic molecules that may have formed.

The objective of the proposed investigation is to estimate bulk density and porosity of outcrops traversed by the Curiosity rover from REMS Ground Temperature Sensor (GTS)-derived thermal inertia and use this information to help evaluate hypotheses for the depositional and diagenetic history of strata in Aeolis Mons. First, a thermal model will be used to derive thermal inertia values for outcrops from GTS diurnal surface temperature measurements. Image-based estimates of sediment cover will help to further refine the models. Next, outcrop thermal inertia values will be compared with laboratory thermal inertia measurements of rocks of known bulk density, porosity and composition, permitting estimates of outcrop bulk density and porosity. These values will then be used to evaluate hypotheses for deposition and diagenesis, with a major focus on the Mg-sulfate units. For example, if sulfates occur as pore-filling, cementing materials, indicative of authigenesis and interaction with fluids in Gale crater, a low porosity and higher bulk density would be expected, consistent with well-cemented sandstones on Earth. Porosity and bulk density would also be expected to vary with sulfate concentration. If the sulfates instead manifest as locally re-worked, airfall, or transported materials, a higher porosity consistent with terrestrial loess or weakly-cemented mudstones or sandstones would be expected, with no correlation between porosity and sulfate abundance.

For select targets sampled by CheMin, laboratory thermal inertia measurements of simulated targets will be acquired, created by synthesizing mineral and amorphous mixtures and compacting them under varying pressures. This dataset will provide a direct comparison to the GTS-derived thermal inertia values for additional constraints on porosity and bulk density.

The proposed investigation provides complementary physical property information to that derived from the powder acquisition drill system (PADS) and rover accelerometer data because TI-based estimates fall at an intermediate spatial scale and depth sensitivity between these two methods.

The investigation will aid in characterizing the geological features contributing to deciphering geological history and the processes that have formed or modified bedrock and regolith, with emphasis on the role of water" (MSL science objective), and therefore is relevant to this call for proposals. Hourly GTS observations are systematically acquired by Curiosity, however, our participation in daily and long-term planning will ensure that optimal observations needed for the robust rock TI estimates are achieved.

Kathryn Stack Morgan/Jet Propulsion Laboratory
Science PI: Rachel Sheppard
Understanding Mg-sulfate distribution, hydration state, and crystallinity in Mt. Sharp

Mg sulfate (MGS) is one of the most common secondary minerals on Mars and is used to constrain Hesperian conditions. The mineralogy of MGS (including its crystallinity and number of structural waters, or hydration state") and its geologic setting can be used to place precise constraints on aqueous conditions during formation and diagenesis. The MSL mission is about to enter the area of MGS-rich strata identified from orbit for the first time, presenting the first opportunity to examine these common martian minerals in situ. The work proposed here will locate scientifically important MGS outcrops, determine the best route to examine them in situ, and conduct a hypothesis-driven science campaign that is synergistic between payload instruments to determine MGS hydration state, crystallinity, and geologic setting, with implications for the broader Gale environment and Mars Noachian-to-Hesperian climatic evolution. We propose four specific Science Tasks to constrain the processes that formed and altered MGS in the near-surface Gale crater environment. (Task 1) We will undertake high-resolution orbital spectral mapping of MGS using processed CRISM and HiRISE data, creating a geologic map of the variation in MGS hydration state in the upper strata around Mt. Sharp. These results will be used to navigate the rover efficiently to high-value targets in the sulfate-rich strata. This orbital perspective of variation within the entire crater (not just along the traverse route) will also add valuable context to variability in fluid conditions through time and space. (Task 2) We will use the rover instrument suite (especially MAHLI images, which allow for calculation of feature size) to document the geologic setting of diagenetic features in situ. This work will be combined with Task 3 to identify which diagenetic features (if any) are MGS-rich. (Task 3) We will document the chemistry, hydration state, and crystallinity of MGS in situ using novel statistical methods performed on ChemCam and APXS elemental abundance data, and repeat observations with ChemCam in concert with DAN to document any (de)hydration that may occur on the martian surface over the course of hours-months. (Task 4) We will synthesize the results from Tasks 1-3 into an updated model of Gale crater aqueous conditions through time and space. These four Science Tasks will be supported by Operations (Task 5) and Dissemination (Task 6) activities to increase the science return and impact of the proposed work. These proposed Tasks will achieve three priorities of this program element: (1) investigation of the types of rock outcrops expected within the Mg sulfate-bearing unit," (2) studies of sediment diagenesis [including] sub-millimeter to centimeter-scale diagenetic features (scales accessible to MSL rover instrumentation) that can occur in mudstone/shale, sandstone, and sulfate-bearing sediments and studies of geochemical changes and/or mineralogical transformations in sedimentary diagenetic environments that might be expected on Mount Sharp," and (3) aqueous geochemistry to constrain fluid conditions through time at Gale crater based on elemental abundances and mineral assemblages measured in Mount Sharp's rock record."

Benjamin Tutolo/Governors of the University of Calgary, The
Model, experiment, and terrestrial analog-informed interpretations of the record of planetary habitability at Mount Sharp

The extension of the Mars Science Laboratory (MSL) mission and its Curiosity rover's exploration of Gale Crater presents exciting possibilities for deciphering the history of the planet's habitability and its potential for having originated life. Sedimentary rocks exposed at the Martian surface offer an information-rich record of the planet's past environmental conditions and biological habitability. Curiosity's expected Extended Mission 4 exploration of unique sedimentological units in Mount Sharp, including proposed interrogation of the so-called Mg-sulfate-bearing unit, Greenheugh Pediment, and Gediz Vallis, offer exciting opportunities for exploring the interplay between climate, water, and biological habitability at the critical time in Mars' past when water-rich conditions existed and hence could have originated life. Yet, the observations that Curiosity will provide must be interpreted within a well-grounded geochemical framework that integrates a process-based understanding of mineral authigenesis and diagenesis; the reaction of igneous minerals and clays with aqueous fluids, and the properties of the resultant fluids and rock; and the interaction between minerals, aqueous fluids, organic molecules, and environmental radiation during planetary processes. This proposal seeks to leverage our team's expertise in quantifying and modeling these geochemical and hydrological processes and Curiosity's prowess as a roving field geologist and mobile geochemical and mineralogical laboratory to develop this framework for accomplishing relevant MSL Mission objectives. To do this, we will use take advantage of our team's and the broader field's recent advances in quantitatively characterizing processes occurring in and below analogous terrestrial lakes and sedimentary strata; calculations of the kinetics and thermodynamics of authigenic and diagenetic mineral formation and transformation; characterization and prediction of organic molecule preservation and degradation in the presence of minerals and environmental radiation. Our specific objectives are to: 1) Understand the significance of clay-sulfate transitions, and their potential, diagenetic contribution to the creation of amorphous materials, in Mt. Sharp sediments and Mars more generally, and 2) Interpret degraded organic molecular signals in an overall geochemical context, including the impact of their interactions with inorganic compounds, fluids, minerals, and environmental radiation. As we seek to meet these objectives, we will work with returned data to: 1): Analyze the textural distributions of observed sedimentary features; 2) Constrain the mineralogical and geochemical makeup of rocks examined during Curiosity's traverse, and 3): Integrate the results of 1) and 2) into geochemical and reactive transport models to develop quantitative constraints on habitability. These investigations will involve active participation in MSL operations by the project team, and will be directly informed by chemical (APXS, SAM, ChemCam, DAN) and mineralogical (CheMin) analyses and imagery (Mastcam, ChemCam, MAHLI) returned by Curiosity. The returned data will be deliberately compiled into individual, investigation-specific data sets and interpreted in the framework of our overall research questions, throughout our participation in the MSL mission which, in turn will enhance the return of the MSL mission.

Scott VanBommel/Washington University

Enhancing the analytical capabilities and science return of Curiosity at Mount Sharp through the application of spectral deconvolution and modeling methods

The primary scientific contributions of this proposal focus on five elements that will directly enhance the scientific capabilities of Curiosity:

1) Provide high-precision geochemistry on a sub-cm scale via APXS spectral deconvolution;
2) Characterize biologically relevant trace elements through spectral modeling and machine learning;
3) Enable mineralogical deconvolution within APXS spectra;
4) Investigate the prevalence and distribution of dust and possible surface coatings through the use of high-throughput X-ray attenuation modeling; and

5) Monitor the condensation flow of atmospheric gases with recurring APXS atmospheric measurements.

The chemical fingerprints of aqueous processes frequently present at scales smaller than the analytical footprint of Curiosity's APXS. High-precision chemistry at the sub-cm scale is enabled through carefully planned APXS rasters and subsequent chemical deconvolution analyses. A focus on deconvolution at the spectral, not oxide, level enables improved accuracy and the possibility to inform distinct endmember compositions, particularly through precise elemental ratios.

Spectral simulation and modeling can facilitate mineral diagnostic capabilities within APXS data, in turn also informing tactical decisions by the CheMin team as to whether or not drilled material should be analyzed given the availability of sample cups. Mineralogical deconvolution within APXS spectra additionally can be utilized to better constrain X-ray amorphous content of past and future drilled materials. Modeling and simulations furthermore enable the quantification of trace elements in APXS analyses near detection thresholds, including trace elements of biological importance not routinely reported. X-ray attenuation modeling enables investigations into layering and surface coatings including dust. Layer models utilizing APXS and ChemCam data can enable insights into material density.

Curiosity's APXS has the potential to monitor fluctuations in non-condensable atmospheric gases with high-frequency. Non-condensable gases, namely Ar, serve as a tracer for condensation flow and thus can provide important ground-truth constraints for Mars climate models, especially when monitored with a regular and frequent cadence.

The contributions proposed will directly advance the mission's goals as well as the goals of NASA and MEPAG. Specifically, deconvolution and modeling work will help characterize geologic features and past processes through enhanced analyses of surface and near-surface materials. The focus on sub-cm scale chemistry additionally aligns with the prioritization of sub-cm diagenetic feature analyses. Modeling work enables the study of additional trace elements that can be used as paleoclimate indicators. APXS atmospheric measurements aid in addressing meteorological goals of the project. Combined, the proposed investigation strengthens the science potential of Curiosity throughout its exploration of the Mg sulfate-bearing unit, the Greenheugh pediment, Gediz Vallis, and beyond.

Amy Williams/University of Florida, Gainesville
Delineating the Sources of Martian Organic Molecules

A variety of organic molecules have been detected in the sedimentary record of Gale crater, Mars. Organics may be generated by exogenous (meteoritic) sources or endogenous (igneous, hydrothermal, or biologic) sources. Any organic macromolecules generated by life may retain biogenic characteristics detectable with gas chromatography-mass spectrometry (GC-MS). The Curiosity rover mission and payload presents the opportunity to search for the source of these organics, specifically with the SAM instrument suite. In particular, the TMAH wet chemistry experiment can hydrolyze and methylate organic macromolecules to release potentially origin-diagnostic molecules for detection with MS.

This study combines data from the Curiosity rover mission payload, and specifically the SAM instrument, to guide optimization of the final SAM TMAH wet chemistry experimental design and uplink scripts (Goal 1.1) and assess the performance of TMAH thermochemolysis on Mg-sulfate Mars-analog standards (Goal 1.2). The PI will serve in a rover operational role to identify highly desirable targets for SAM wet chemistry as outlined in Goal 1. The PI will work with the SAM team and Sulfate-Unit Campaign leads during operations to identify highly desirable targets (leveraging findings from Goal 1.2) for the final TMAH experiment (Goal 2) Finally, the PI will perform higher fidelity analysis of the first TMAH experiment from the Mary Anning target (Goal 3.1) and leverage findings from Goal 3.1 to perform high fidelity analyses of the second TMAH experiment after it is executed in the sulfate-bearing unit (Goal 3.2).

This work will serve a significant need within the SAM instrument team and the mission will benefit from having these data presented first-hand at rover Science Discussions and team meetings. The data from this investigation will be paramount in determining the source of organics on Mars' near surface, and for optimizing the parameters for the last TMAH experiment onboard SAM.

The PI is prepared to participate in Science Team meetings and train for operational roles such as a SOWG Chair, Geology Science Theme Lead, or as a Long-Term Planner. The goals of this work are relevant to the goals of NASA and the Mars Exploration Program, as well as several MSL science objectives including characterization of organic compounds and potential biomarkers in representative bedrock and regolith, and identification and quantitative assessment of "taphonomic windows" for organic carbon. Lastly, this work will support the scientific training of early career graduate students.

Analog Activities to Support Artemis Lunar Operations: Desert RATS 2022
Abstracts of Selected Proposals
(NNH21ZDA001N-DRATS)

Below are the abstracts of proposals selected for funding for the Analog Activities to Support Artemis Lunar Operations: Desert RATS 2022 program. Principal Investigator (PI) name, institution, and proposal title are also included. Thirty-two proposals were received in response to this opportunity. On May 6, 2022, ten proposals were selected for full funding.

James Bell/Arizona State University
Using Scientific And Operational Techniques Learned From Rover Missions To Support Artemis Science Objectives And Traverse Planning

It has been nearly 50 years since human exploration of the Moon or other planetary body beyond Earth. In that time, NASA has launched increasingly complex spacecraft missions including fly-bys, orbiters, and landed missions that have provided an abundance of scientific and operational lessons learned. Rovers like Curiosity and Perseverance are the closest thing to field geology that NASA has done since the Apollo missions ended. As a team member of the science and operations teams for both rovers I plan to use lessons and techniques learned from operating the rovers to help prepare for the future of human space exploration. Combining this knowledge with my prior field experience and scientific expertise would make me a valuable contribution to the Desert Research and Technology Studies 2022 field season. My field work experience includes numerous trips around the Hawaiian Islands, New Zealand, and Flagstaff, AZ. As a participant in this analog exercise, I will help NASA prepare for geologic exploration of the Moon and beyond as part of the Artemis missions.

Ernest Bell/University of Maryland, College Park
Geophysical, Operations, And Engineering Cross-Discipline Support Combination For Nasa D-RATS Field Campaign

The conducting of analog simulations on the Earth are an excellent and proven method for testing scientific, operational, and engineering concepts for planetary exploration to develop improved methods and hardware that increase the probability of success for a space mission. The Desert Research and Technology Studies (D-RATS) is a series of human lunar surface analog tests that began in the late 1990s. The upcoming 2022 field campaign is a high-fidelity human lunar surface exploration analog mission simulation to be conducted near the SP Crater and/or Black Point Lava Flow (BPLF), Arizona.
For this field campaign, PI Dr. Bell proposes to support the pre-mission identification and integration of science objectives into the analog mission activity plan to formulate the

analog mission traverse within the overarching strategic questions being addressed by this test. This support will include participating virtually in the planning phase through the spring and summer of 2022, and in-person at the NASA Johnson Space Center (JSC) for a dry run of the test activities to assess the hardware and operational readiness of the analog mission. During the simulated mission, Dr. Bell will fill the role of a member of strategic and/or tactical mission science teams, field observer, field participant, or a combination of these roles at either NASA JSC, the SP Crater area, or both depending on the specific roles assigned.

Upon completion of the simulated analog mission, Dr. Bell proposes to work with other members from the D-RATS team to formulate a manuscript to provide improved understanding and guidance for the interwoven mission challenges addressed by science, operations, and engineering teams. By taking into consideration the best practices and activity categorizations gleaned from this field test, a recommendation for a concept of science operations for human lunar surface exploration will be provided.
In addition, the results will be incorporated into Dr. Bell's post-doctoral research with the NASA SSERVI GEODES team conducted at the NASA Goddard Space Flight Center through the University of Maryland CRESST II consortium. In this position Dr. Bell is completing studies on geophysical field techniques for planetary surface exploration using analog locations on Earth. The recommendations of best practices and categorization of activities concluded from the D-RATS participation will be merged into his research with the SSERVI GEODES team.

Lauren Edgar/USGS Flagstaff
Participation and Field Analog Support for Artemis Lunar Operations

The proposed work would support PI Edgar to participate in NASA's Desert Research and Technology Studies (D-RATS) field campaign. PI Edgar brings relevant field experience, having led numerous training trips to similar areas near SP Crater and Black Point Lava Flow, and developing field guides and resources for the proposed sites. Edgar also brings significant operations experience from the Mars Exploration Rovers and Mars Science Laboratory missions in both tactical and strategic roles. She has a demonstrated record of working effectively in diverse team settings, in the field and through mission operations. The PI hopes to participate in the D-RATS analog field campaign to contribute to decisions regarding the hardware, software, and operations structures for lunar exploration, and how to maximize the support provided by a science team in mission control. Furthermore, the experience gained through D-RATS would be mutually beneficial to current training activities involving NASA astronauts, engineers, and managers, as well as other research projects. PI Edgar would be happy to participate in either field operations in Flagstaff or the science backroom. If selected, the PI plans to participate in the dissemination of results by contributing to NASA reports, conference presentations and/or manuscripts to describe the lessons learned from these field campaigns.

The proposed work is relevant to the D-RATS opportunity because it would involve participation in the D-RATS field analog exercise and would result in feedback provided to NASA regarding concepts of operations with specific relevance to support science operations." The PI hopes to bring her field expertise in volcanic and sedimentary environments, mission operations experience, knowledge of training activities, and experience working effectively on diverse teams to contribute to field analog support for Artemis lunar operations through D-RATS.

Amy Fagan/Western Carolina University
Justification and Rationale for Selection to Participate in the 2022 Desert Research and Technology Studies (D-RATs) Field Campaign

My interest in participating in the 2022 D-RATS analog field campaign is guided by two main desires: (1) to support Artemis and (2) to increase the ability of the LEAG chair to act as an effective tie between the NASA and non-NASA lunar community. My past and current experiences with field work and working in diverse teams, along with my expertise in extraterrestrial samples and a clear plan of disseminating results, will allow me to be an effective science support team-member and to contribute to the 2022 Desert Research and Technology Studies (D-RATS) campaign to enhance science return from Artemis.

Field work and the broad ability to collaborate with others are essential skills that any geologist and planetary scientist should have and nourish. I have experience in a variety of field locations with different team structures and regularly guide groups of undergraduate students in the field to learn about geologic processes, conducting proper field work, and how to approach/design a field-based research project; student learning outcomes from these are regularly assessed. I develop and apply metrics to assess student learning outcomes and I am familiar with common metrics used in analog studies (e.g., EAMD SDQ). Although I use metrics to assess students, these are not altogether different from some metrics used in analog studies such as D-RATS and other similar projects. My expertise lies in geochemical and petrological sample analysis of extraterrestrial materials, especially those of lunar origin (Apollo and meteorites), and I am an Apollo Principal Investigator. I clearly did not collect these precious samples, but I can apply my knowledge of lunar samples to help work towards better metrics for evaluating sample collection in D-RATS and for enhancing future Artemis missions.

It is important to work with other people with different backgrounds, as diversity of thought and lived experiences lead to stronger programs and new ideas. I have experience working in teams of various sizes and composition with people of many different backgrounds as a professor, former Geology Program Director, and the chair of the Lunar Exploration Analysis Group (LEAG). In addition, I value the establishment of an Equity, Diversity, and Inclusion (EDI) Chair for LEAG and look towards her guidance as we move towards a more inclusive model for space exploration.

I plan to take a multi-step approach towards conveying the results of the field campaign to the broader community as well as potential recommendations for the future. Through active collaboration with other participants in D-RATS, I plan to generate an abstract for the Lunar and Planetary Science Conference as well as submit of a manuscript of findings and recommendations from the field campaign.

Brent Garry/NASA Goddard Space Flight Center
Participation in Desert RATS 2022

Analog field campaigns are critical to develop and test science operations concepts for planetary surface missions. High fidelity field tests forge teamwork between scientists, engineers, and mission operations. Desert Research and Technology Studies (Desert RATS) 2022 will fuel creativity needed to anticipate Artemis lunar surface science operations with purposeful activities driven by relevant science objectives within the timeframe of a possible mission scenarios. As a member of the science team, I will apply various aspects of my background in field geology, field instruments, geologic mapping, geographic information systems (GIS), lunar research, and analog field tests to the planning, execution, and analysis of the Desert RATS 2022 field campaign. My primary interest is assisting the Desert RATS team in the development of surface science scenarios and assessments of science payloads for upcoming lunar mission planning.
Field Research: My geologic training and expertise are in volcanology, geomorphology, and field geology with applications to lunar volcanism. Essentially, my field research focuses on morphologic comparisons to formulate eruption scenarios for lunar volcanic features. I have conducted volcanic field studies in Hawai'i, New Mexico, Idaho, California, Arizona, Oregon, Iceland, and the Galapagos. Field projects involve planning multi-week field projects (remote sensing, traverses, timelines), travel and equipment logistics, and team safety.

Analog Experience: I have participated in analog field campaigns since 2003 as a crewmember and member of the science backroom: Mars Desert Research Station (2003-2006), Moon and Mars Analog Mission Activities (2008-2009), NASA Desert RATS (2008-2011), and BASALT (2015-2017).

One of the underlying drivers of my field research during my career has been to apply my field experiences to understand the challenges of field work on the Moon or another planetary body. My motivation to participate in the Desert RATS 2022 field campaign is to apply my collective experiences from field work, geologic mapping, lunar research, virtual reality/augmented reality (AR/VR), and past analog campaigns to inform lunar science operations for the Artemis program. Areas where I could be effective as a science team member are:
1) Surface Science Scenarios: Anticipate possible lunar surface operation situations to define surface science scenarios to test during the field campaign.
2) Instrument manifest: to a mission and the development of Ops Cons to best utilize those instruments to meet science objectives

3) Traverse planning: Use and evaluate GIS tools and data products for planning and to follow along with real-time operations and how to handle lunar lighting and terrain challenges.
4) Human-Robotic collaborations: How to utilize robotic assets during a mission and EVA.
5) EVA Imagery Data Products: Create data products from photographs collected during each EVA (annotated mosaics, sketch maps) similar to Apollo preliminary science reports.
6) AR/VR: Understand how AR or VR can be used by the science team for planning, spatial awareness of science operations during the mission, and post-mission visualization of science stations, as a way to revisit the field site.

My areas of expertise are in volcanology, geomorphology, and comparative planetology and are directly relevant to the geologic context of the Desert RATS 2022 field site. My background in lunar data analysis and mapping lunar terrains, including the distribution of boulders at the lunar south pole and updating the geologic maps of the Apollo 15-16-17 landing sites can be applied to the development of surface science scenarios based on lunar geology.

After the field campaign, I will participate in team debriefs and evaluations, write a white paper for internal use and sharing within the Artemis planning teams, lead author a paper, and contribute content to team abstracts and publications.

Jose Hurtado/University Of Texas, El Paso
Analog Activities to Support Artemis Lunar Operations: Desert RATS 2022

This proposal is my application to participate in the Desert RATS 2022. I have 25+ years of field geology experience and have participated in numerous analog activities. These include: Desert RATS 2009-2012; field testing of the NASA Ames K-10 robotic rover; the HI-SEAS Mars analog missions in Hawai'i; and the field activities of the RIS4E/RISE2 SSERVI team. My roles in these analog studies have ranged from participation on the science teams, including traverse/mission planning and real-time mission support; crew member for rover, habitat, and EVA operations; and evaluator of operations activities. Along with my field geology and analogs experience, I have effectively worked with diverse teams, in academic, NASA, and industry settings. If selected, I would provide expertise in field geology as well as operations experience gained from my previous analog work. To ensure timely reporting of results and feedback to NASA, I advocate sessions organized by the Desert RATS team for the Lunar Surface Science Workshops series as well as other venues, in addition to publications.

Shannon Nawotniak/Idaho State University
Science participation in the 2022 D-RATS analog field campaign

This proposal is an application to join the science team for the 2022 D-RATS analog field program. I am a physical volcanologist with extensive field and planetary analog experience, having participated in the BASALT, SUBSEA, and FINESSE analogs in addition to my normal field research. I have a history of working successfully in large and small groups that span disciplines and racial/ethnic identities. I desire to be part of the D-RATS science team because of the opportunities it affords to support the larger Artemis program and to develop new collaborations and research proposals for planetary analog research. If selected for participation, I commit to disseminating results and lessons learned through journal articles and white papers, inclusion in an upcoming planetary analog textbook for which I am under contract as an author and editor, and community outreach.

Jacob Richardson/NASA Goddard Space Flight Center
Supporting Crewed Geology Field Research in Preparation for Artemis

Crewed operations at the lunar surface will enable geology field research on the Moon for the first time in a generation. Since Apollo, a paradigm shift in field geology has occurred, which has made portable science instruments ubiquitous in the field, enabling real-time analysis of geophysical, geochemical, and high-resolution topography properties of field sites. As technological advances in field research have fundamentally changed how field researchers operate on Earth's surface, geology operations during Artemis will also increase in complexity compared to Apollo missions.

PI Richardson has over a decade of field research experience and has led science investigations at planetary analog field sites at a wide variety of destinations including the San Francisco Volcanic Field (SFVF) in Flagstaff Arizona, which is the target of the 2022 Desert RATS field test. PI Richardson's geology research foci include the formation and evolution of volcanic terrains on planetary bodies such as the Moon and Mars, which well prepares him to be a subject matter expert for the geology that will be encountered by Desert RATS. PI Richardson is currently a leader within two large and diverse field analog science teams: Richardson is the Deputy PI of the Geophysical Exploration Of the Dynamics and Evolution of the Solar System (GEODES) node of NASA's Solar System Exploration Research Virtual Institute (SSERVI); and Richardson is currently the lead of the Goddard Instrument Field Team (GIFT) at NASA Goddard Space Flight Center. These diverse and multi-disciplinary teams both address outstanding questions and Strategic Knowledge Gaps (SKGs) to enable exploration on planetary surfaces through field analog research.

As a planetary analog field scientist, PI Richardson is dedicated to ensuring the application of state-of-the-art field research practices to crew-supported investigations on the lunar surface. PI Richardson is involved with Artemis-relevant instrument concepts and knows first-hand that instrument concepts still await mission architecture decisions that affect designs, which DRATS projects will help determine. As a DRATS team member, PI Richardson will help in the construction of documents detailing lessons learned and related findings during and after the main DRATS field test. As a DRATS team member, Richardson expects to help in writing and sometimes presenting conference abstracts to disseminate findings.

James Skinner/USGS Flagstaff
"Supporting Artemis Through Analog Operations: Desert Research and Technology Studies (D-RATS)"

PI has diverse field experience acquired both prior to and during his career in the planetary sciences, including extended offshore seismic campaigns and previous D-RATS efforts. PI has worked effectively in a range of team settings through field campaigns and through his role as coordinator for the Planetary Geologic Mapping Program. PI's background experience in geologic mapping, field work, analog research, logistical planning, community training, and knowledge of the geology, access, and hazards associated with the BPLF/SP potential traverse envelope make him an excellent candidate to participate in the D-RATS 2022 activities. PI understands the need for clearly conveying scientific and technical results, particularly when they are closely paired as in analog activities in preparation for off-world exploration. This proposal will demonstrate that the PI has unique fundamental and applied science experience, the ability to work within a range of team settings, and experience with preparing and disseminating review and guidance documents, each of which solidly supports the intent and evaluative merit of the D-RATS 2022 analog activities, as described in the solicitation.

R Yingst/Planetary Science Institute
Testing Tension Points: A Proposal for Desert RATS 2022 Participation

In Artemis, science avatars will include humans, robots, and human-tended instruments in a way no previous mission has. I propose to use my science operations experience and operations testing expertise to fully support the Desert RATS field analog tests so they may yield robust results. I will help develop and exercise science team operations procedures to evaluate their efficacy, identify and remove or mitigate tension points, and increase efficiencies.

OSIRIS-REx Sample Analysis Participating Scientist Program
Abstracts of selected proposals
(NNH21ZDA001N-ORSAPSP)

Below are the abstracts of proposals selected for funding for the ORSAPSP program. Principal Investigator (PI) name, institution, and proposal title are also included. 48 proposals were received in response to this opportunity. On July 25, 2022, 8 were selected for funding.

Kun Wang/Washington University
The Moderately Volatile Element Isotopic Compositions of Bennu and Their Implication on the Asteroid s Volatile Depletion History

SCIENCE GOALS AND OBJECTIVES: We propose to analyze the isotopic compositions of moderately volatile elements (MVEs) in the returned Bennu sample from the OSIRIS-REx mission to investigate its nebular and parent-body alteration history, its relation to known meteorites, and the effects of space weathering. For this, we will focus on four MVEs (K, Zn, Cu and Rb) which cover a wide range of volatility and geochemical affinity. Furthermore, these MVEs are sensitive to vaporization processes and their isotopes have been shown to be robust tracers for deciphering distinct volatile depletion events. In the case of chondrites, different chondrite groups show distinct MVE isotopic compositions (e.g., a dichotomy between carbonaceous and ordinary chondrites). Thus, measuring the MVE isotopes of the returned Bennu sample and comparing them with those of known chondrites (measured by the PI's group or from literature) would help in testing the hypothesis that Bennu's parent body formed beyond the snow line. In addition, aqueous alteration on the parent body and meteorite impacts would generate further isotopic signatures to different degrees for the four MVEs studied here. Thus, by modeling the four MVEs together, we can distinguish nebular and parent-body fractionation events and constrain the conditions in which these MVEs were depleted or fractionated.

METHODOLOGY: Overall, we will analyze the bulk chemical and isotopic compositions of MVEs in the Bennu sample. First, we will completely digest the bulk sample (0.05g minimal; 0.2g ideal) using a HF-HCl-HNO3 mixture. Second, a 10% aliquot (if the sample is 0.05 mg, less if we obtain more) of the digested sample will be analyzed for 47 major and trace elemental compositions using a Q-ICP-MS (Quadrupole Inductively Coupled Plasma Mass Spectrometer). Third, based on the concentrations measured using Q-ICP-MS, we will divide the remaining solution into several aliquots for moderately volatile element isotope (K, Zn, Cu and Rb) analyses using a MC-ICP-MS (Multi-Collector Inductively Coupled Plasma Mass Spectrometer). All the instruments are housed in our department and supervised by the PI, with major and trace elemental analysis and K, Zn, Cu and Rb isotope analyses routinely carried out. Meteorite analogs (e.g., CI and CM chondrites) will be processed and analyzed for comparison. Geological reference materials will also be measured for quality control.

RELEVANCE: This proposed research will directly analyze the material returned by OSIRIS-Rex and will address one of the baseline science requirements of the OSIRIS-REx mission during the sample-analysis phase of the project (Section 1.2 of C.30): Analysis of the returned sample to determine the nebular and parent-body alteration history; the relation to known meteorites; and space weathering. This proposed research will test three hypotheses outlined in the PIP and Sample Analysis Plan: Hypothesis #1 (Remote sensing of Bennu's surface has accurately characterized its mineral, chemical, and physical properties), #4 (Bennu's parent body formed beyond the snow line by accretion of material in the protoplanetary disk), and #10 (The physical, chemical, and spectral properties of Bennu's surface materials have been modified by exposure to the space environment).

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Amy Hofmann/Jet Propulsion Laboratory
Constraining the origins and thermal histories of aliphatic and aromatic hydrocarbons from Bennu via measurements of their site-specific and clumped isotopic compositions

Reconnaissance imaging by the OSIRIS-REx Visible and InfraRed Spectrometer (OVIRS) and Thermal Emission Spectrometer (OTES) revealed Bennu to be compositionally akin to the CI and CM carbonaceous chondrites, with detailed analyses of OVIRS absorption spectra indicating the presence of aliphatic and aromatic CH bonds. The most abundant aromatic hydrocarbons extracted from CI and CM meteorites include the PAHs pyrene and fluoranthene; their compound-specific carbon and hydrogen isotopic compositions point to extraterrestrial origins, while relationships between their 13C/12C ratios and total carbon number suggest possible formation pathways. Aliphatic hydrocarbons, including n-alkanes, have also been extracted from carbonaceous chondrites and their identities and abundances used to argue for surface-mediated Fischer-Tropsch-type reactions; however, compound-specific 13C/12C and D/H ratios suggest that these extracts may be mixtures of terrestrial contaminants and indigenous meteoritic organics, thus leaving open the question of extraterrestrial reaction pathways.

The goal of this work is to elucidate such pathways for the aliphatic and aromatic hydrocarbons found on Bennu, identify the conditions under which those compounds formed, and, by extension, determine their provenance. This work thus presents an opportunity to investigate Bennu's 'organic history' and to explore the relationship between pristine asteroidal hydrocarbons and comparable compounds extracted from carbonaceous chondrites.

As detailed in the OSIRIS-REx Sample Analysis Plan, the Science Team intends to perform molecule-averaged compound-specific isotope analyses (CSIA) of Bennu's organic compounds including D/H of PAHs. Although such analyses can confirm extraterrestrial origins, using those data to infer formation environments and genetic relationships among compounds often leads to non-unique interpretations. We propose to go beyond CSIA by characterizing the intramolecular isotope distributions of the most-abundant aromatic and aliphatic hydrocarbons from Bennu's soluble organic matter (SOM). These include site-specificity (i.e., differences in isotopic composition between structurally inequivalent sites in the same molecule) and multiple substitutions ('clumped': two or more rare isotopes present in the same molecule). Site-specific 13C and D distributions in n-alkanes have been used to infer formation (and destruction) pathways, while 'clumping' in various compounds has been shown to reflect temperatures of homogeneous equilibrium, mechanisms of irreversible reactions, and fractionations due to kinetic processes. Site-specific and clumped isotope compositions of Bennu's hydrocarbons will thereby provide more definitive information on the compounds' origins (and potential evolution) than that garnered from CSIA alone.

We will use high-precision, high-accuracy Orbitrap mass spectrometry (MS) to measure the clumped and, where appropriate, site-specific carbon and hydrogen isotopic compositions of the most abundant aromatic and aliphatic hydrocarbons from Bennu. Due to its exceptionally high mass resolution, large mass range, and capability for simultaneous evaluation of multiple peaks, Orbitrap MS is uniquely positioned to resolve isobaric interferences that other MS techniques cannot, including the quantitative resolution of multiply-substituted species while requiring only 10s of picomoles of analyte. The analytical capabilities of this method have been demonstrated on organic molecules, including aromatic compounds and amino acids extracted from the Murchison meteorite.

The proposed work addresses four of the OSIRIS-REx Level-1 hypotheses (2, 3, 4, and 5) focused on identifying the sources of Bennu's organic matter (3.4, 4.3, 5.3) and its similarity to that in CI and CM chondrites (2.3). As such, we will join the Sample Organic Analysis Working Group and engage with the Sample Element and Isotope Working Group as appropriate.

OSIRIS-REx Sample Analysis Participating Scientist Program
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Ashley King/NASA Foreign PI Support Organization
Unlocking Bennu's Past: Aqueous and Thermal Alteration from the Mineralogy and Water Contents of Returned Samples

Unlocking Bennu’s Past: Aqueous and Thermal Alteration from the Mineralogy and Water Contents of Returned Samples

Primitive asteroids that avoided melting and differentiation represent the original building blocks of the Solar System and are key for understanding the formation and evolution of planets. The Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer (OSIRIS-REx) spent nearly two years investigating the carbonaceous asteroid (101955) Bennu, identifying widespread hydrated silicates, carbonates, and organic-rich phases on the surface. In September 2023, OSIRIS-REx will return to Earth with pristine samples collected from the regolith of asteroid Bennu. Laboratory analyses of the returned samples, which will be unmodified by the terrestrial environment and have crucial geological context, will transform our knowledge of conditions in the early Solar System and the origin of habitable planets like Earth.

The overall objective of this project is to determine the nature, degree, and relative timing of aqueous and thermal alteration on asteroid Bennu, providing fundamental constraints on its initial composition and past geological activity.

This will be achieved by using non-destructive, correlated scanning electron microscope imaging and energy-dispersive X-ray spectroscopy (SEM-EDS), micro X-ray computed tomography (μCT), and synchrotron tomographic methods (contrast imaging, XRD, XRF and XANES) to investigate fine and coarse Bennu particles. In addition, fines and powdered Bennu samples will be characterized using a combination of position-sensitive-detector X-ray diffraction (PSD-XRD) and thermogravimetric analysis (TGA).
Task 1: Characterize the mineralogy, textures, chemical composition, and oxidation state of fine and coarse Bennu particles. This task will constrain the nature, geochemical conditions, and relative timing of aqueous, thermal, and impact processing on Bennu.
Task 2: Determine the modal mineralogy of coarse Bennu particles. This task will constrain the extent of aqueous alteration and thermal metamorphism, and test predictions about Bennu’s mineralogy determined by remote sensing observations.
Task 3: Quantify the hydration state of coarse Bennu particles. This task will investigate the carrier phases of volatile species on Bennu and place additional constraints on the degree of aqueous and thermal alteration.

This project is directly relevant to the OSIRIS-REx mission objective to “Return and analyze a sample of pristine carbonaceous asteroid regolith” in order to study its composition and history. Together, the proposed tasks address major hypotheses related to the “Fundamental Nature of Bennu” (specifically, 1.1, 1.2, 1.3, 1.4), “The Pre-accretionary Epoch” (4.3), “The Parent-Body Epoch” (5.2, 5.3, 5.5), and “The Bennu Epoch” (7.4).

The PI and Co-Is will also contribute to the mission through their knowledge and expertise in the preparation and analysis of extraterrestrial materials and the processing and interpretation of mineralogical and chemical datasets.

OSIRIS-REx Sample Analysis Participating Scientist Program
Abstracts of selected proposals
(NNH21ZDA001N-ORSAPSP)

Below are the abstracts of proposals selected for funding for the ORSAPSP program. Principal Investigator (PI) name, institution, and proposal title are also included. 48 proposals were received in response to this opportunity, 8 of which were selected for funding.

Katherine Freeman/Pennsylvania State University
Advanced Organic Isotope Studies of
Asteroid Bennu Samples from OSIRIS-REx

We propose high sensitivity and position-specific isotope analyses of insoluble and soluble organic constituents of Asteroid Bennu. The proposed methods will enable highly precise measurements (1 sigma = 10) for 100 picomoles of C in molecules, for C and N isotopologues of 10s of nanomoles of target compounds, and for organic C, S, and N in < 1-mm diameter particles or grains. In the contingency case of high sample mass return, we will pair these with C and N-isotope analyses at high spatial resolution (15-mm) using SIMS. Surface processes, alteration, and/or weathering losses have potentially reduced recoverable organics on Bennu. The proposed methods address this challenge and enhance data prospects that will allow exploration across a continuum of chemical scales and heterogeneities and provide valuable clues to the origins and alteration of potentially pre-biotic compounds in our solar system.

Proposed instruments include the nano-EA/IRMS, which is a modified elemental analyzer (EA) coupled to an isotope-ratio-mass spectrometer (IRMS) for analyses of small solid samples and isolated molecules. With pico-CSIA, we can make compound-specific isotope analyses (CSIA) of picomolar quantities using a streamlined GC-combustion interface to an IRMS. It also has significantly improved separation power than is typical for compound-specific isotope analyses and conventional GC methods, which enables analyses of minor constituents or complex mixtures of prebiotically relevant compounds. Intramolecular isotope patterns will be evaluated using Orbitrap MS, taking advantage of its high mass resolution and mass accuracy to evaluate isotope ratios from fragment or molecular ions. We will use a bespoke peak trapper" inlet that enables expanded observation times needed for isotopologue analyses. Sample size requirements depend on molecule ionization and fragmentation properties; for 13C and 15N, they generally match conventional CSIA methods (i.e., 10s of nanograms).

Together, the compound-specific and isotopologues studies can reveal C and N sources captured within organic molecules, as shown for substrates used in Strecker synthesis of alanine in the Murchison meteorite. Alteration reactions under warm, aqueous conditions can be reflected in relationships between carboxyl and inorganic C isotopes. And, given the 0.3 to 0.6 estimated H/C ratio detected by the OVIRS, we propose to evaluate parent, alkylated, or heteroatomic aromatic hydrocarbons (PAH), which represent IOM building blocks potentially cleaved, altered, and released into SOM via radiation exposure. These structures document chemical relationships between IOM and SOM that lend insights to the origins and history of organics on the asteroid.

The proposed suite of bulk, molecular, and isotopologue analyses complement already planned observations involving SOM and IOM in returned samples and are therefore fully consistent with the objectives of the OSIRIS-Rex Sample Analysis Participating Scientist Program (ORSA-PSP). Proposed analyses will support ORSA-PSP baseline requirements for evaluation of the organic history, including isotopic imprints from early warm/wet conditions, and subsequent heating and space weathering under variable exposure and resurfacing conditions, as articulated in Driving Hypotheses 2, 3, 9, 10, and 11 in the Sample Analysis Plan (OSIRIS-Rex Sample Analysis Team, 2022). If awarded, the first year will be devoted to rigorous checks involving meteoritic samples and to building a strong collaboration with the OSIRIS-REx organic and isotope teams (SOAWG; SEIWG) to refine and coordinate material and molecular analyses.

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Yongsong Huang/Brown University
Prebiotic synthesis of volatile organic compounds: molecular and compound-specific isotopic analyses of OSIRIS-Rex return samples

The prime objective of the proposed study is to analyze the distribution and compound-specific isotopic composition of volatile organic compounds in materials returned by OSIRIS-REx. Volatile organic compounds (hydrocarbons, monocarboxylic acids, ketone/aldehydes, amines, esters, alcohols) are fundamental building blocks for more complex organic compounds such as amino acids found in great abundance in carbonaceous meteorites. The low molecular weight monocarboxylic acids, for example, are the most abundant soluble organic compounds in Murchison (10 to 100 times more abundant than amino acids). Our previous research from Murchison has shown enormous structural diversity of monocarboxylic acids and, based on their isotopic compositions, suggested substantial interstellar heritage especially for C1 to C4 homologues. However, due to their high volatility, it is unclear, and perhaps controversial to argue, that the volatile organic compounds are of principally interstellar origin, which would imply that these compounds survived (rather than produced by) the highly turbulent processes of protoplanetary disk formation and the subsequent chemical processes taking place on and within asteroid parent bodies. The pristine sample from Bennu offers an unprecedented opportunity to study the origin and evolutionary processes of prebiotic organic compounds, building upon the knowledge and experience obtained previously from carbonaceous chondrites.

The proposed work will perform streamlined analyses of the following classes of volatile organic compounds: hydrocarbons, monocarboxylic acids, ketones, aldehydes, amines, esters, ethers and alcohols. We will take advantage of latest analytical technologies for volatile organic compounds including direct thermal extraction, solid phase micro-extraction, purge-and-trap to transfer these compounds to GCMS and GCIRMS for structural and compound specific carbon, hydrogen and nitrogen (in case of amines) analyses. To minimize sample consumption, we have performed initial test using the latest inert, high-performance GC capillary columns that permit direct separation and analyses of different polar volatile compounds (acids, amines, ketones, alcohols) without derivatization. We estimate our approach reduces the sample consumption by at least 5 fold relative to published methods that derivatize individual polar volatile compound classes. Simultaneous (and non-destructive) characterization of sample lithology, mineralogy and elemental compositions will be carried out on the same sample to help assess the relationship between volatile organics and inorganic substrates. These aspects, and the need to focus on pristine samples, make this work relevant to the objectives of the OSIRIS-REX sample analysis participating scientist program.

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Gerardo Dominguez/University Auxiliary and Research Services Corporation
Big Science From Small Samples: A Multi-Technique Approach for Understanding Bennu s Formation and Alteration History at the Nanoscale

Here, we propose to augment the existing capabilities of the OSIRIS-REx team by carrying out a coordinated set of measurements of Bennu samples (and controls) using NanoIR techniques, including both scattering-type, scanning near-field optical microscopy (s-SNOM) and nanoscale photothermal IR spectroscopy (AFM-IR). The NanoIR measurements will be connected to synchrotron-based far-field IR, as well as ground truth mineralogy/petrology using Scanning Electron Microscopy with Energy Dispersive Spectroscopy (SEM-EDS), Transmission Electron Microscopy (TEM), Scanning Transmission X-ray Microscopy (STXM), and Nanoscale Secondary Ion Mass Spectrometry (NanoSIMS) to provide a complete picture of the organic and mineral composition of the Bennu samples at the nanoscale. The entire experimental chain can be done using inert atmosphere and vacuum in order to eliminate oxidation and terrestrial modification of the samples. As part of our sample analysis chain, we propose to use witness samples to monitor the rate of atmospheric oxidation of Bennu samples at the nanoscale using NanoIR.

Because NanoIR is non-destructive, and we have an air-free chain, our inclusion as Participating Scientists would provide nanoscale infrared support to other members of the OSIRIS-REx team who can benefit from our capabilities and experience, particularly in the handling and imaging of small samples. Because we have access to both types of NanoIR, and the advantages of each, we provide the full suite of IR analysis, including the ability to measure thin radiation damaged layers in situ, and measure the real part of mineral optical constants both of which can be important for interpreting remote sensing results.

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Greg Brennecka/Lawrence Livermore National Laboratory/Dept of Energy
Ancient tales from the isotopics of pristine material

Synopsis and relevance: This proposal requests three years of funding to investigate the constituent materials, formation history, and evolution of the asteroid Bennu. Broadly, this will be accomplished by measuring chemical and isotopic signatures of separated phases and bulk material returned from Bennu's surface. The work proposed here is relevant to the call, as it seeks to layer chemical and isotopic data obtained from a single sample aliquot to address several of the baseline science requirements of OSIRIS-REx, including the: 1) relationship to known meteorites, 2) space weathering, and 3) resurfacing history of Bennu.

Bennu's relationship to known meteorites is best addressed by analyzing isotopic signatures of nucleosynthetic origin for which specific isotope ratios are distinctive for different meteorite groups. In addition to duplicating many of the planned isotopic investigations of the Science Team, we will conduct isotopic measurements of multiple elements (e.g., Sr, Mo, Ba, Nd, Sm, Gd, Er, Yb, Hf) at the requisite precision from a single aliquot. This combined elemental suite represents a wide range of geo- and cosmochemical behaviors as well as isotopes formed by various nucleosynthetic processes. Therefore, these elements are integral for Solar System reconstructions and establishing Bennu's relationship to other known samples and, ultimately, determining where Bennu formed in the Solar System.

Of the isotopic systems mentioned above that will be used to assess the genetic heritage of Bennu, some isotopes also double as neutron dosimeters. Specifically, the surface evolution of planetary materials can be examined using the isotopic compositions of elements affected by cosmic ray irradiation, a phenomenon that can lead to secondary neutron capture reactions. The isotopes 149Sm, 155Gd, and 157Gd have large thermal neutron capture cross-sections, while 167Er and 177Hf have a high probability of capturing epithermal neutrons. We have developed Monte Carlo simulations using the abundances of these isotopes in conjunction with trace element abundances of the bulk sample to determine the neutron fluences, thermal/epithermal neutron ratios, and energy profiles. This will constrain the exposure history of the samples on the surface of the parent body, informing us about the space weathering and resurfacing environment on Bennu.

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Kees Welten/University of California, Berkeley
Investigating the recent resurfacing history of asteroid Bennu based on cosmogenic radionuclide measurements in samples returned by OSIRIS-REx

Observations by NASA's OSIRIS-REx spacecraft of asteroid Bennu during the approach and surveying phases of the mission revealed evidence that this small rubble pile asteroid experiences several active surface processes that likely control the recent surface exposure history of Bennu. In October 2020, the spacecraft successfully collected a surface sample from a relatively young ~20 m diameter crater on asteroid Bennu that will be returned to Earth in September 2023. Our goal is to understand the recent exposure history of surface samples of asteroid Bennu utilizing radionuclides (10Be, 26Al, 36Cl, 41Ca) produced by cosmic rays, both galactic (GCR) and solar (SCR). With half-lives ranging from 0.1 to 1.36 million years (Myr), the concentrations of these cosmogenic nuclides provide information on the duration and exposure conditions (irradiation depth) of these samples on a timescale of a few Myr, i.e., similar to the time period in which Bennu is believed to have been dynamically decoupled from the main asteroid belt. These measurements are complimentary to the planned gamma-ray measurements of a bulk sample which will mainly yield activities of short-lived nuclides (22Na, 60Co and 44Ti) as well as long-lived 26Al, and are also complimentary to the noble gas measurements which will yield a total cosmic-ray exposure time for each sample. Since each radionuclide has a different production rate depth profile, several radionuclides are required to derive both irradiation time and depth, especially when irradiation conditions have changed during the last few Myr of exposure. The measurement of multiple nuclides with different half-lives and different production mechanisms provides an excellent framework to address the surface exposure history of the samples as a function of meteoroid impacts or downslope mass movement. Recent improvements in sample preparation techniques as well as upgrades in the accelerator mass spectrometry (AMS) facility have increased sensitivity of the radionuclide measurements by an order of magnitude, allowing measurements of 10Be, 26Al and 36Cl in samples of less than 1 mg, including individual grains, while 41Ca measurement require samples of ~50 mg. These radionuclide measurements on regolith samples from Bennu will provide information on surface processes on a million-year timescale that can be compared with timescales inferred from theoretical models of recent crater formation and mass movement on asteroid Bennu. The proposed work will test several of the driving hypotheses about Bennu's evolution, including 11.1 Hokioi crater is part of a population of small (25 m) red craters on Bennu that are less than 0.1 Myr old and 11.3. Material from regions upslope and north migrated into Hokioi Crater and material originally within the crater migrated downslope and to the south. Constraining the timescale of this mass movement is also relevant to hypothesis 9.3 Bennu's surface experienced mass movement that transported material from the mid-latitude to the equatorial region over the past 0.2 Myr. The cosmogenic radionuclide measurements will thus provide more constraints on the nature of surface processes on asteroid Bennu. The proposed research is relevant to NASA's strategic goal to understanding and solving the mysteries of outer space based on the analysis of returned samples in Earth-based laboratories.
