Table of Contents - HPD

7. Heliophysics Division (HPD)

7.a. Demographics

7.a.i. Principal Investigators (PIs)

7.a.i.1. Limitations of the data - HPD 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 Heliophysics Division, there are ~3,300 submitted proposals over all ROSES years: ~2,900 for ROSES 2016-2020 and ~400 for ROSES 2021.

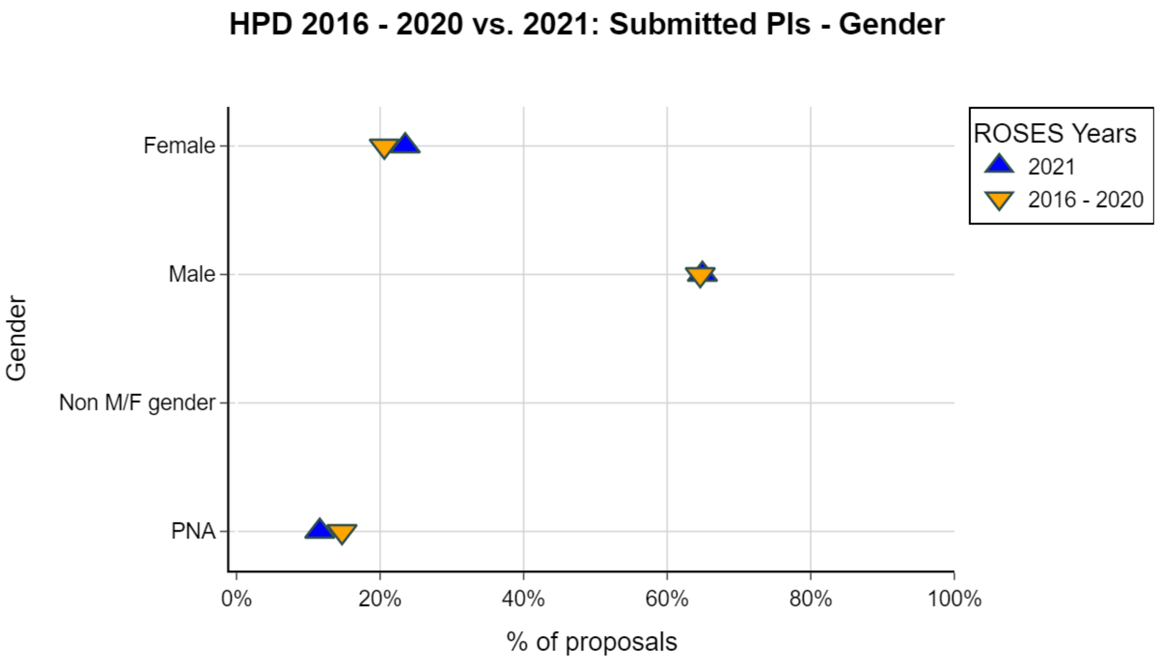
Proposals with PIs who took the survey but selected "prefer not to answer" for all demographic survey questions:

- Submitted proposals: HPD 2016 - 2020: 13% | HPD 2021: 10%
- Selected proposals: HPD 2016 - 2020: 12% | HPD 2021: 9%

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.

7.a.i.2. Gender - HPD PIs

HPD 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.

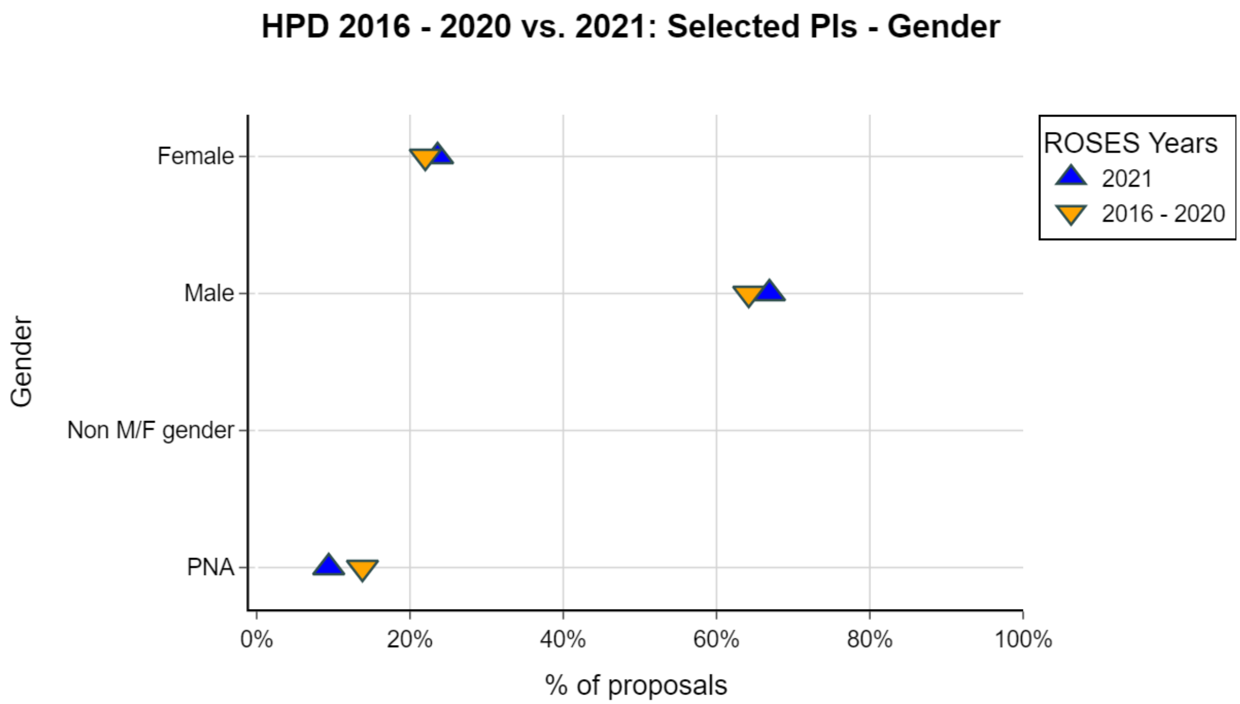
HPD PIs: Submitted Gender - Data Table

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

Gender	HPD 2016 - 2020	HPD 2021
Female	21%	24%
Male	65%	65%
Non M/F gender	NR	NR
PNA	15%	12%

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

HPD 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.

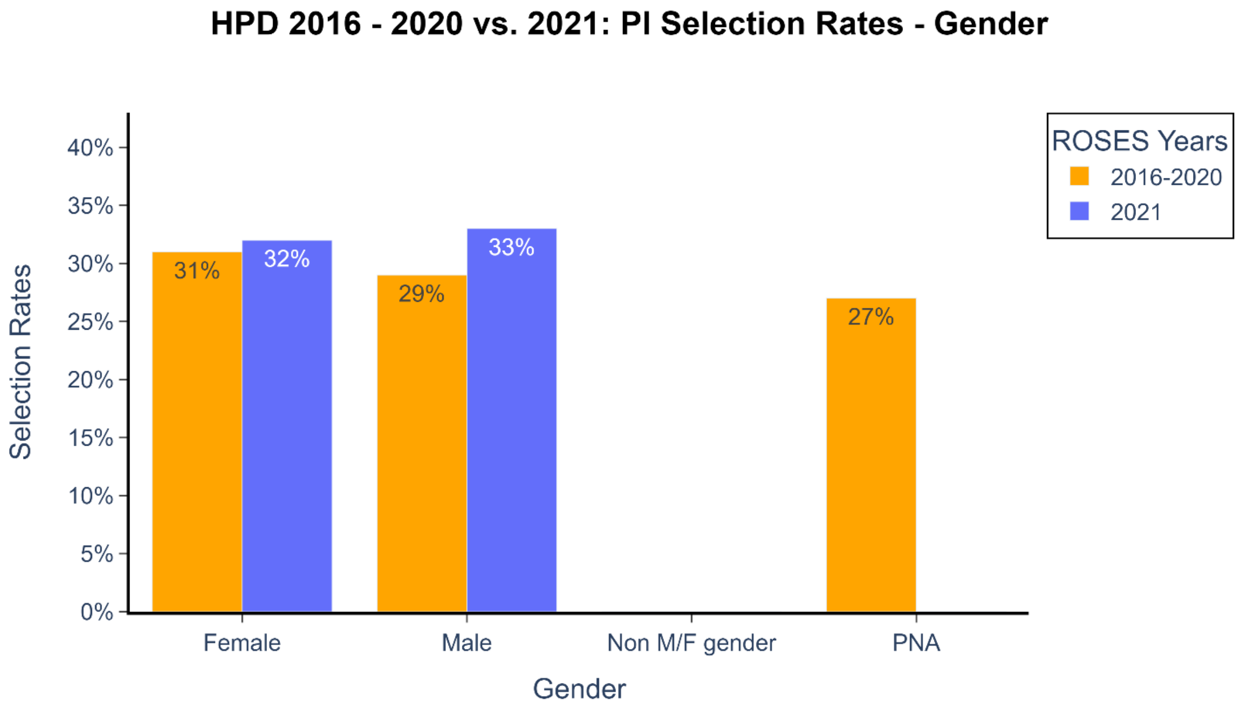
HPD PIs: Selected Gender - Data Table

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

Gender	HPD 2016 - 2020	HPD 2021
Female	22%	24%
Male	64%	67%
Non M/F gender	NR	NR
PNA	14%	9%

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

HPD 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), PNA (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.

HPD PIs: Gender Selection Rate - Data Table

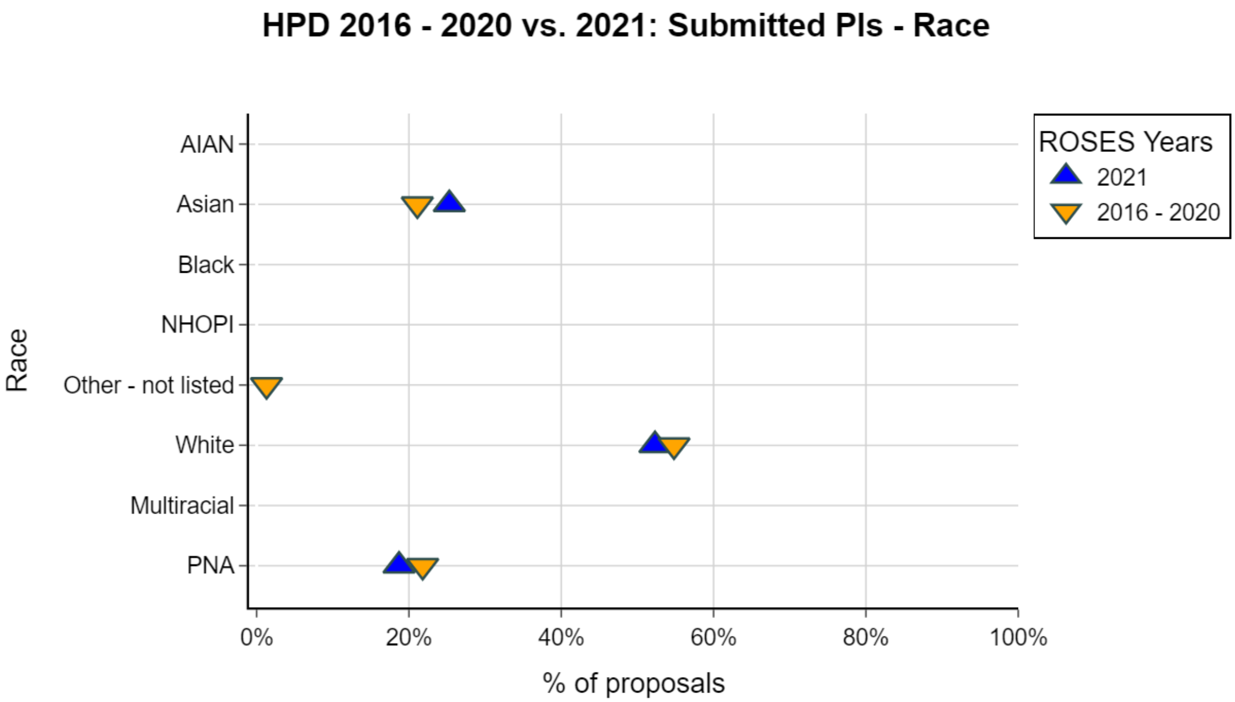
HPD 2016 - 2020 vs. 2021: PI Selection Rates - Gender

Gender	HPD 2016-2020	HPD 2016-2020 Response/All Genders	HPD 2021	HPD 2021 Response/All Genders
Female	31%	1.07	32%	1
Male	29%	1	33%	1.03
Non M/F gender	NR	NR	NR	NR
PNA	27%	0.93	NR	NR
All Genders	29%	1	32%	1

PNA: Prefer not to answer | NR: Non 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

7.a.i.3. Race - HPD PIs

HPD 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 (All years), NHOPI (All years), Other – not listed (ROSES 2021), Multiracial (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.

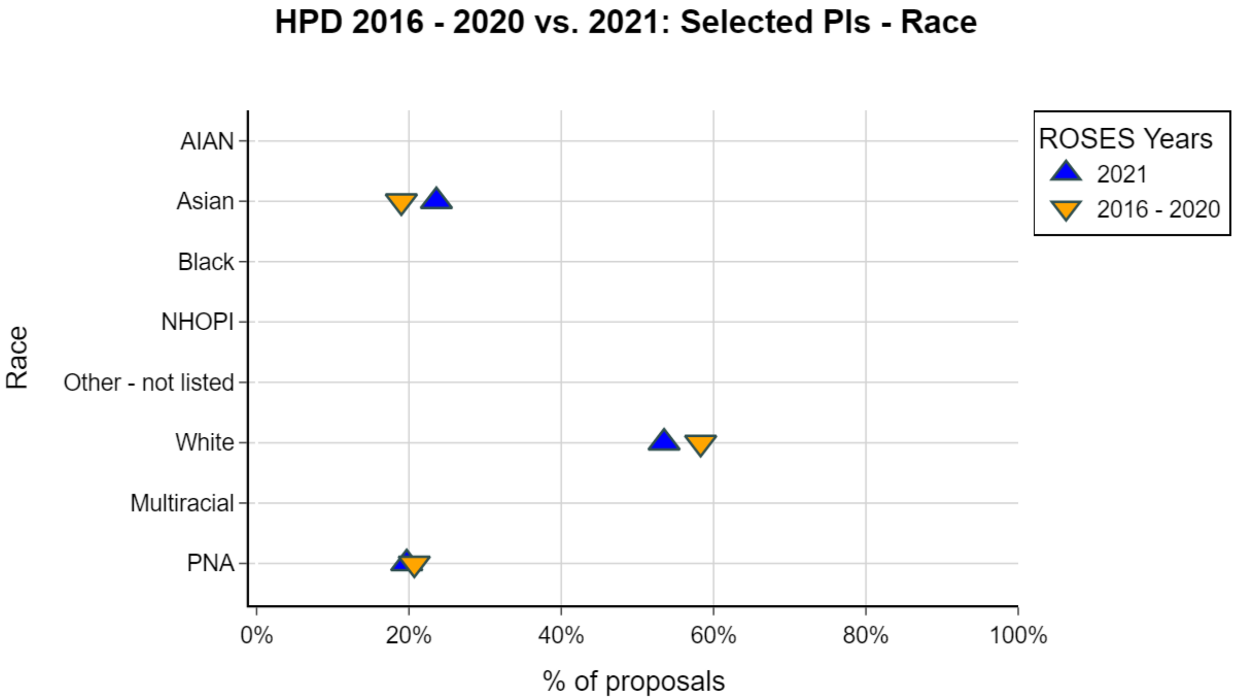
HPD PIs: Submitted Race - Data Table

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

Race	HPD 2016 - 2020	HPD 2021
AIAN	NR	NR
Asian	21%	25%
Black	NR	NR
NHOPI	NR	NR
Other - not listed	1%	NR
White	55%	52%
Multiracial	NR	NR
PNA	22%	19%

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

HPD 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 (All years), Multiracial (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.

HPD PIs: Selected Race - Data Table

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

Race	HPD 2016 - 2020	HPD 2021
AIAN	NR	NR
Asian	19%	24%
Black	NR	NR
NHOPI	NR	NR
Other - not listed	NR	NR
White	58%	54%
Multiracial	NR	NR
PNA	21%	20%

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

HPD 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 (All years), Multiracial (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.

HPD PIs: Race Selection Rate - Data Table

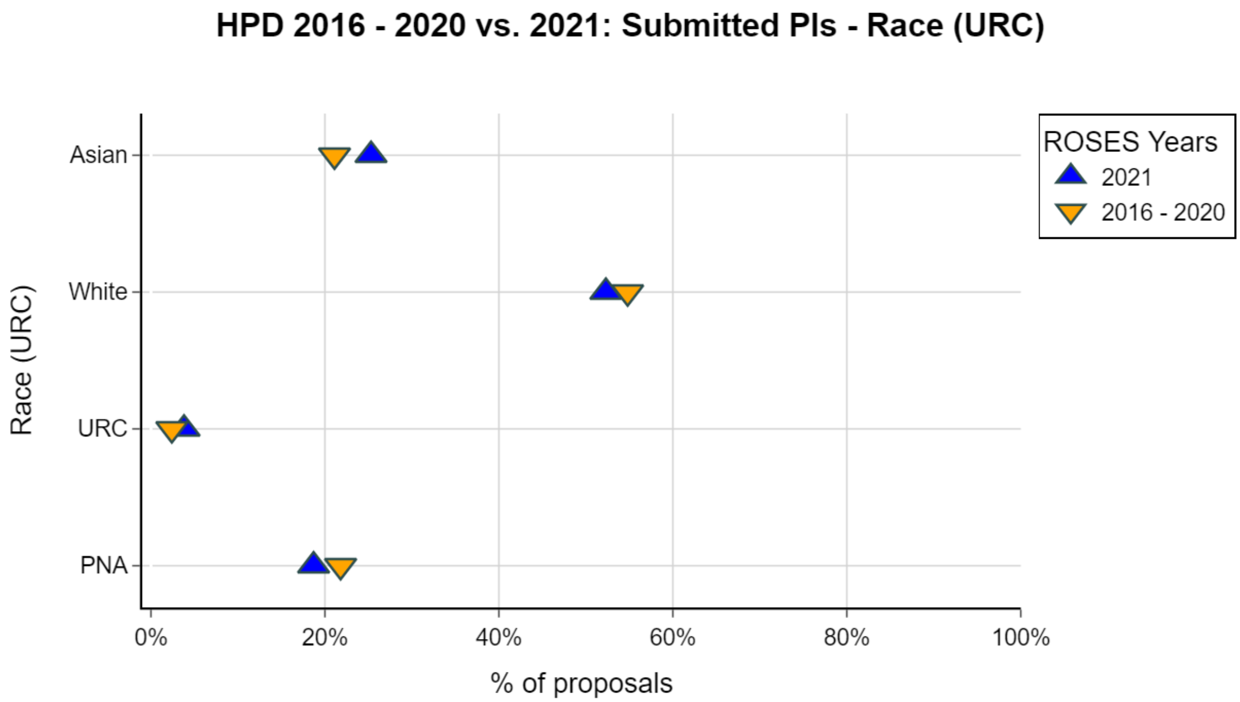
HPD 2016 - 2020 vs. 2021: PI Selection Rates - Race

Race	HPD 2016-2020	HPD 2016-2020 Response/All Races	HPD 2021	HPD 2021 Response/All Races
AIAN	NR	NR	NR	NR
Asian	26%	0.9	30%	0.94
Black	NR	NR	NR	NR
NHOPI	NR	NR	NR	NR
Other - not listed	NR	NR	NR	NR
White	31%	1.07	33%	1.03
Multiracial	NR	NR	NR	NR
PNA	27%	0.93	34%	1.06
All Races	29%	1	32%	1

AIAN: American Indian and Alaska Native | NHOPI: Native Hawaiian and Other Pacific Islander | PNA: Prefer not to answer | NR: Non 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

7.a.i.4. Race using Under-Represented Community (URC) - HPD PIs

HPD PIs: Submitted 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.

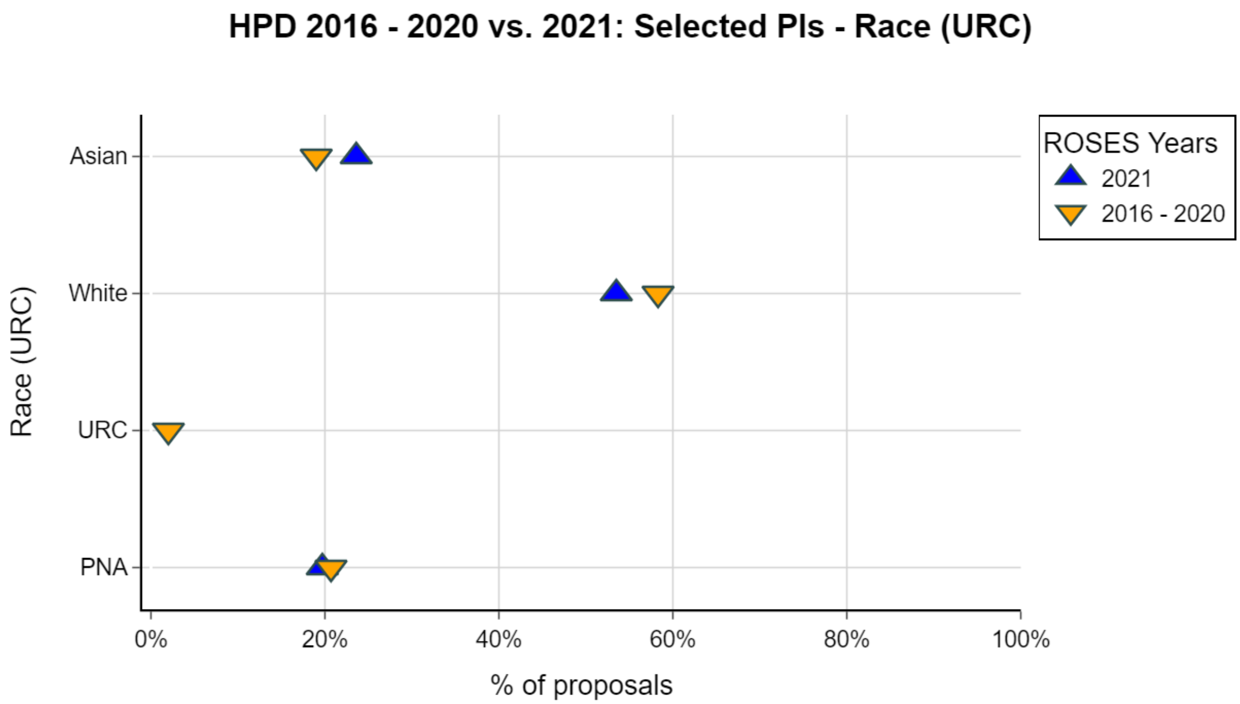
HPD PIs: Submitted Race (URC) - Data Table

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

Race (URC)	HPD 2016 - 2020	HPD 2021
Asian	21%	25%
White	55%	52%
URC	2%	4%
PNA	22%	19%

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

HPD 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.

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.

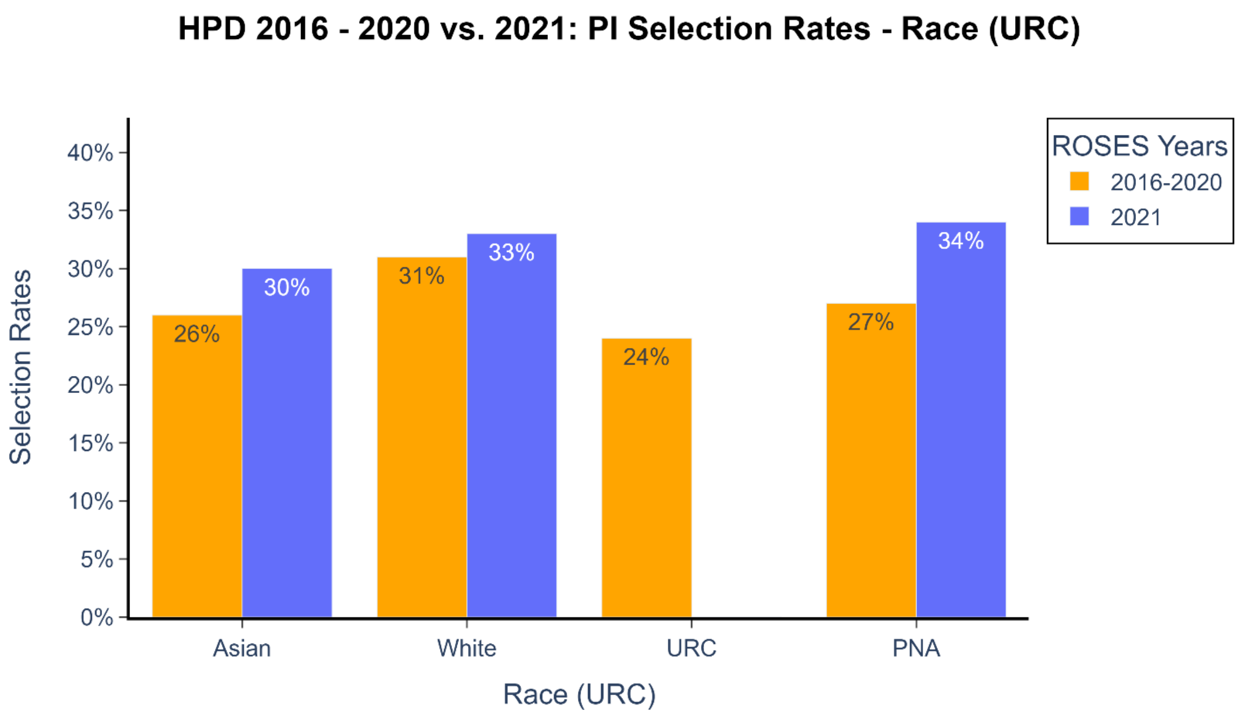
HPD PIs: Selected Race (URC) - Data Table

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

Race (URC)	HPD 2016 - 2020	HPD 2021
Asian	19%	24%
White	58%	54%
URC	2%	NR
PNA	21%	20%

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

HPD 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.

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

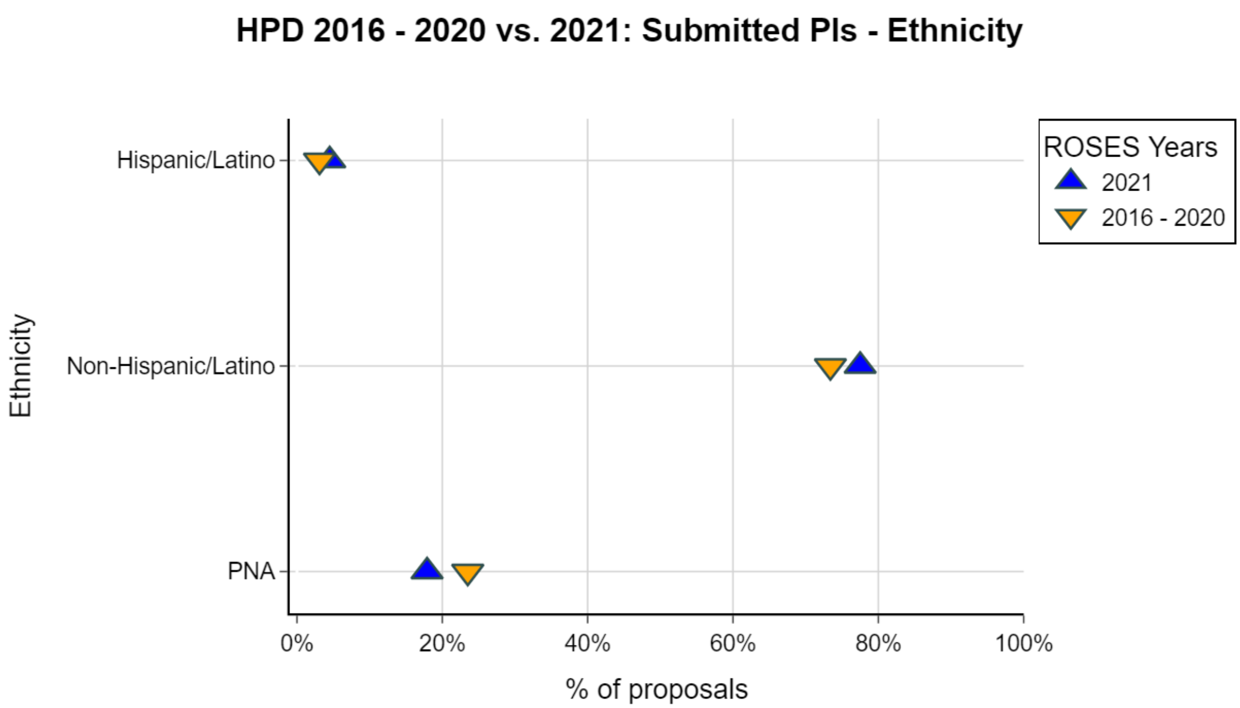
HPD 2016 - 2020 vs. 2021: PI Selection Rates - Race (URC)

Race (URC)	HPD 2016-2020	HPD 2016-2020 Response/All Races (URC)	HPD 2021	HPD 2021 Response/All Races (URC)
Asian	26%	0.9	30%	0.94
White	31%	1.07	33%	1.03
URC	24%	0.83	NR	NR
PNA	27%	0.93	34%	1.06
All Races (URC)	29%	1	32%	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: Non 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

7.a.i.5. Ethnicity– HPD PIs

HPD PIs: Submitted Ethnicity - Plot



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

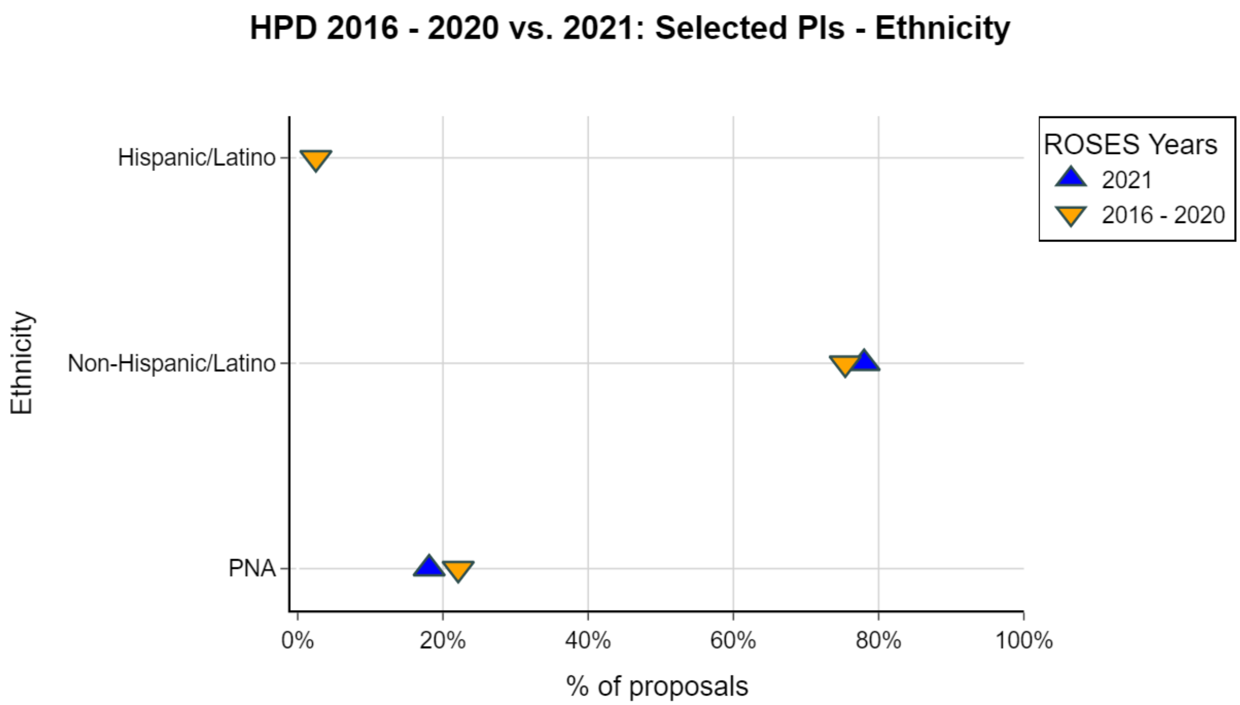
HPD PIs: Submitted Ethnicity - Data Table

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

Ethnicity	HPD 2016 - 2020	HPD 2021
Hispanic/Latino	3%	4%
Non-Hispanic/Latino	73%	78%
PNA	24%	18%

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

HPD 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.

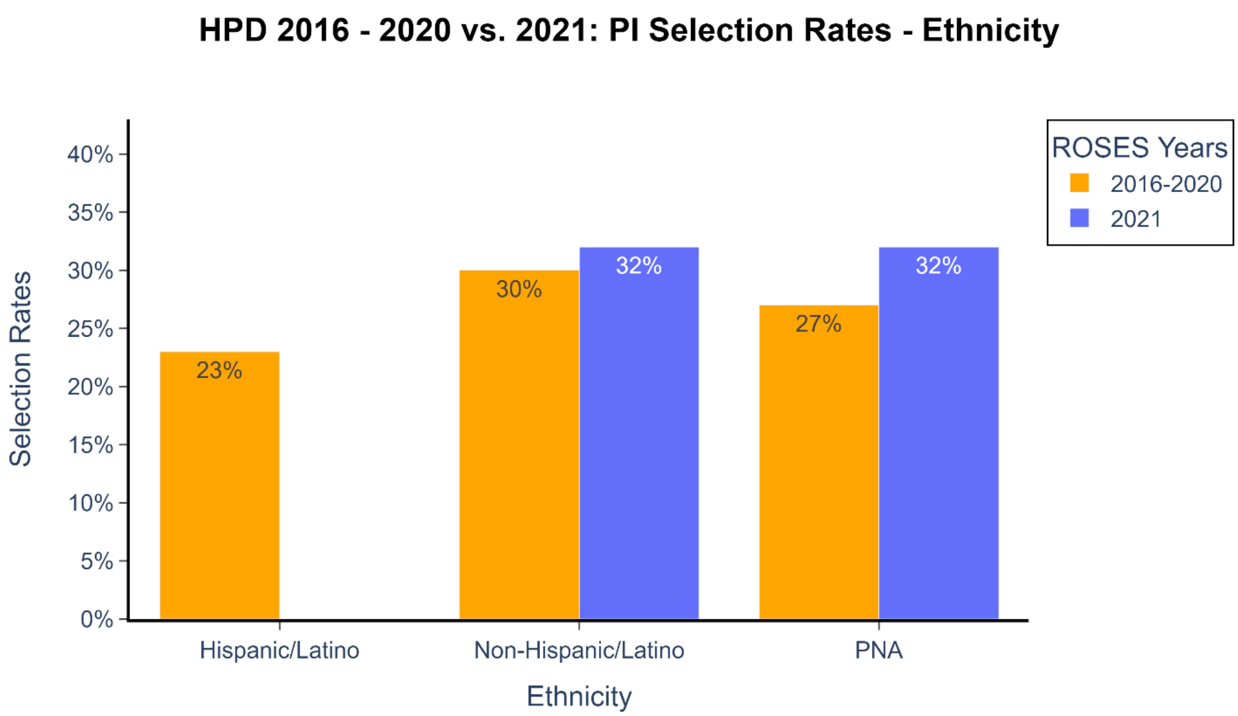
HPD PIs: Selected Ethnicity - Data Table

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

Ethnicity	HPD 2016 - 2020	HPD 2021
Hispanic/Latino	2%	NR
Non-Hispanic/Latino	75%	78%
PNA	22%	18%

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

HPD 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.

HPD PIs: Ethnicity Selection Rate - Data Table

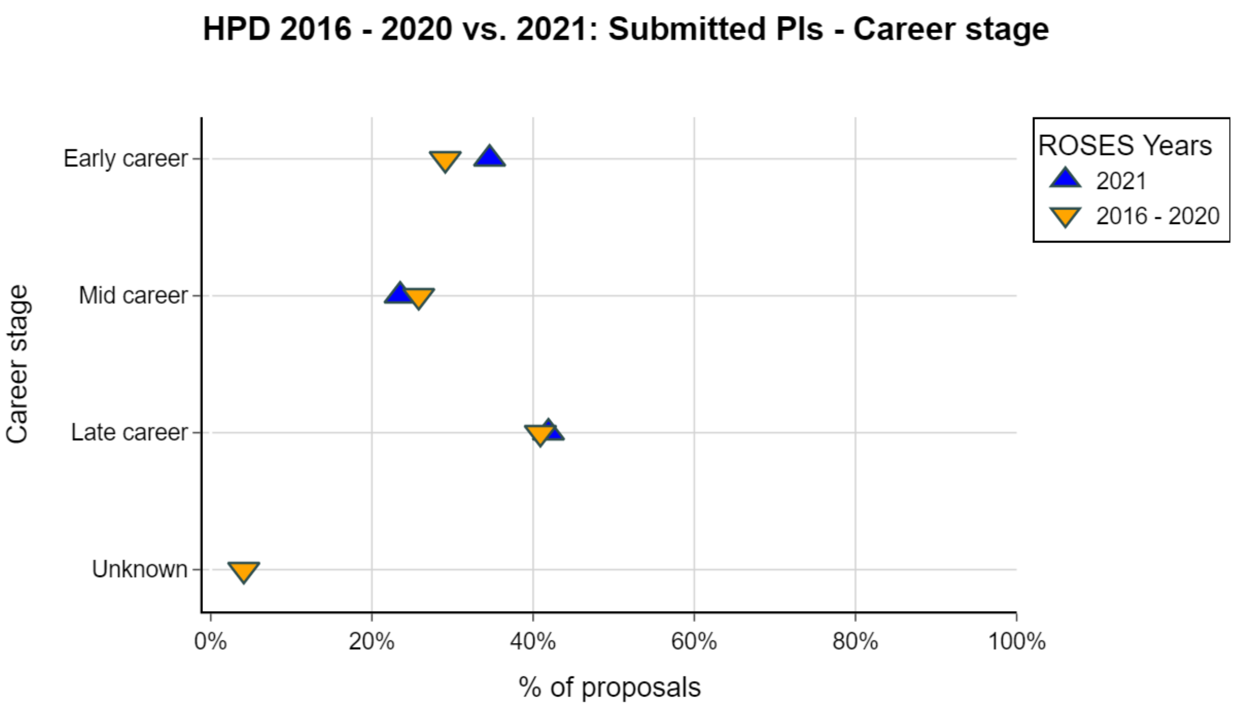
HPD 2016 - 2020 vs. 2021: PI Selection Rates - Ethnicity

Ethnicity	HPD 2016-2020	HPD 2016-2020 Response/All Ethnicities	HPD 2021	HPD 2021 Response/All Ethnicities
Hispanic/Latino	23%	0.79	NR	NR
Non-Hispanic/Latino	30%	1.03	32%	1
PNA	27%	0.93	32%	1
All Ethnicities	29%	1	32%	1

PNA: Prefer not to answer | NR: Non 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

7.a.i.6. Career Stage - HPD PIs

HPD 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.

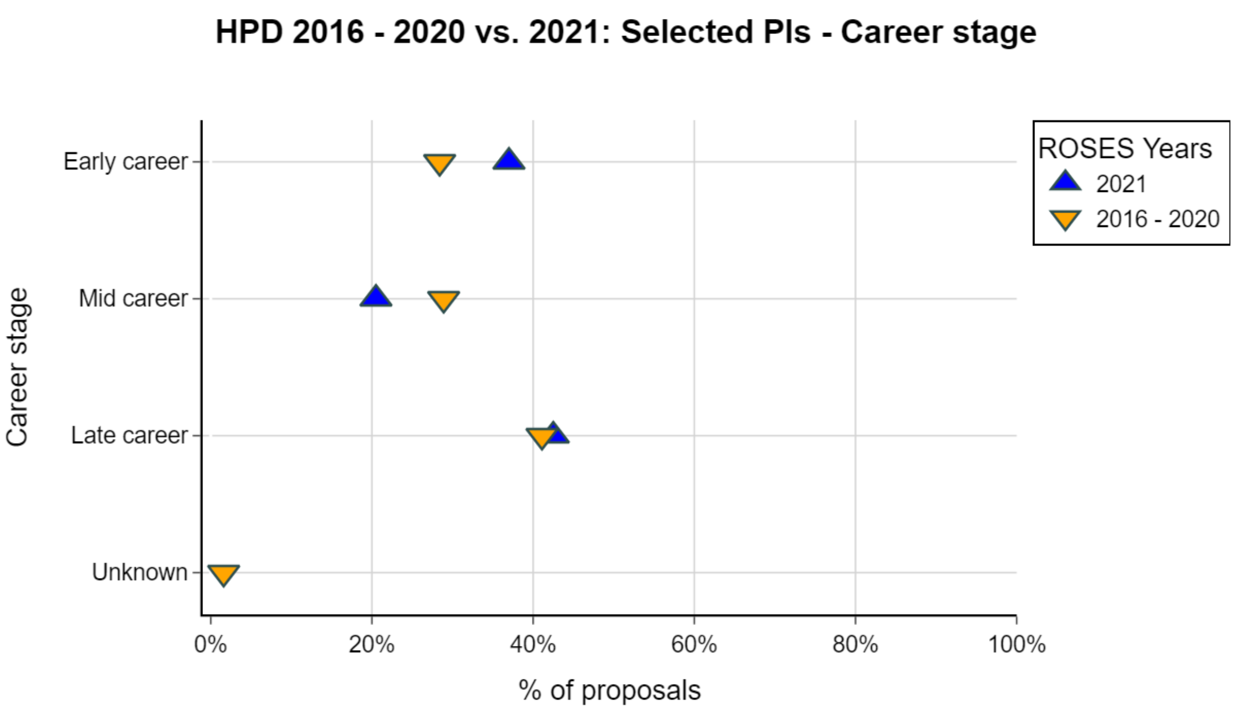
HPD PIs: Submitted Career Stage - Data Table

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

Career stage	HPD 2016 - 2020	HPD 2021
Early career	29%	35%
Mid career	26%	24%
Late career	41%	42%
Unknown	4%	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: Non reportable | ROSES 2016-2020 proposal data are aggregated.

HPD 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.

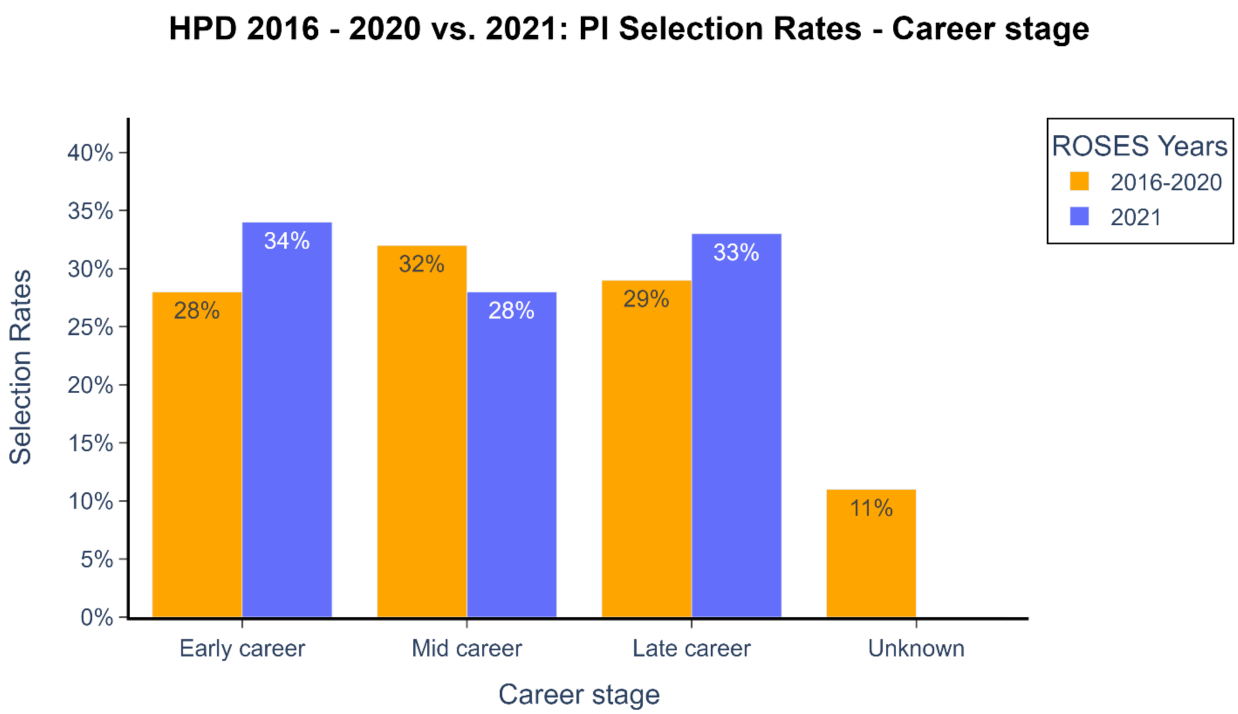
HPD PIs: Selected Career Stage - Data Table

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

Career stage	HPD 2016 - 2020	HPD 2021
Early career	28%	37%
Mid career	29%	20%
Late career	41%	42%
Unknown	2%	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: Non reportable | ROSES 2016-2020 proposal data are aggregated.

HPD 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.

HPD PIs: Career Stage Selection Rate - Data Table

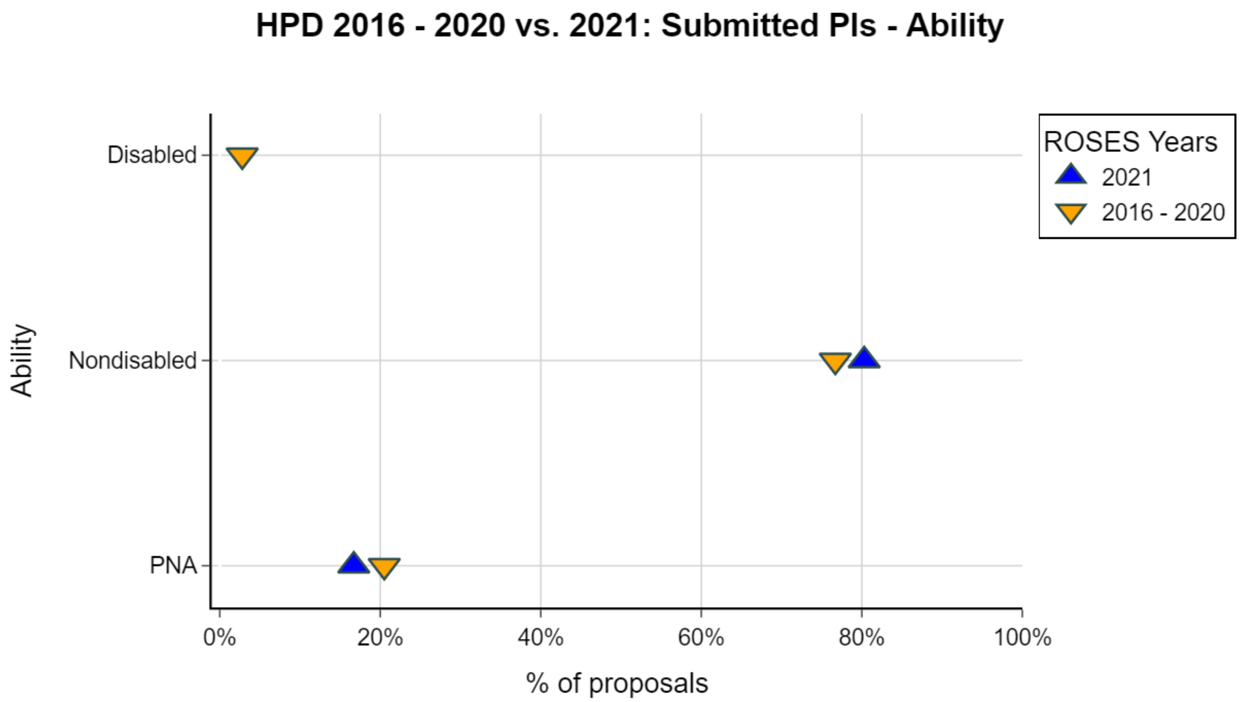
HPD 2016 - 2020 vs. 2021: PI Selection Rates - Career stage

Career stage	HPD 2016-2020	HPD 2016-2020 Response/All Career stages	HPD 2021	HPD 2021 Response/All Career stages
Early career	28%	0.97	34%	1.06
Mid career	32%	1.1	28%	0.88
Late career	29%	1	33%	1.03
Unknown	11%	0.38	NR	NR
All Career stages	29%	1	32%	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: Non 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

7.a.i.7. Disability Status– SMD PIs

HPD 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.

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.

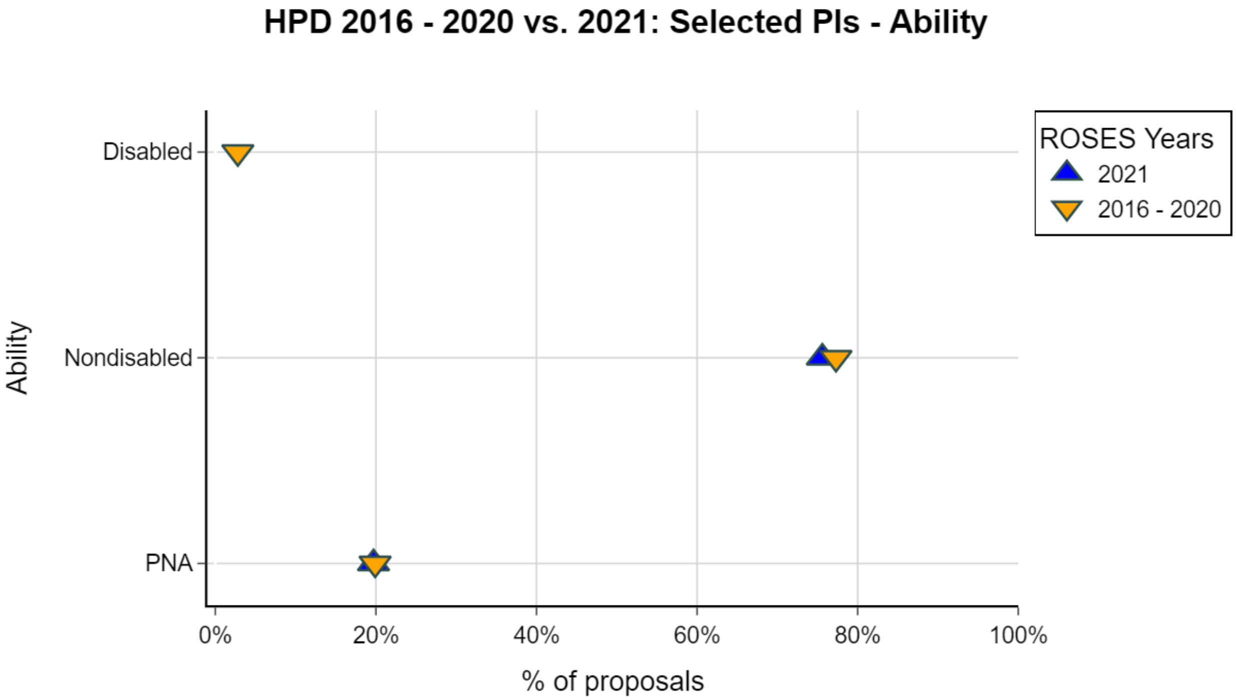
HPD PIs: Submitted Ability - Data Table

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

Ability	HPD 2016 - 2020	HPD 2021
Disabled	3%	NR
Nondisabled	77%	80%
PNA	20%	17%

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

HPD 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.

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.

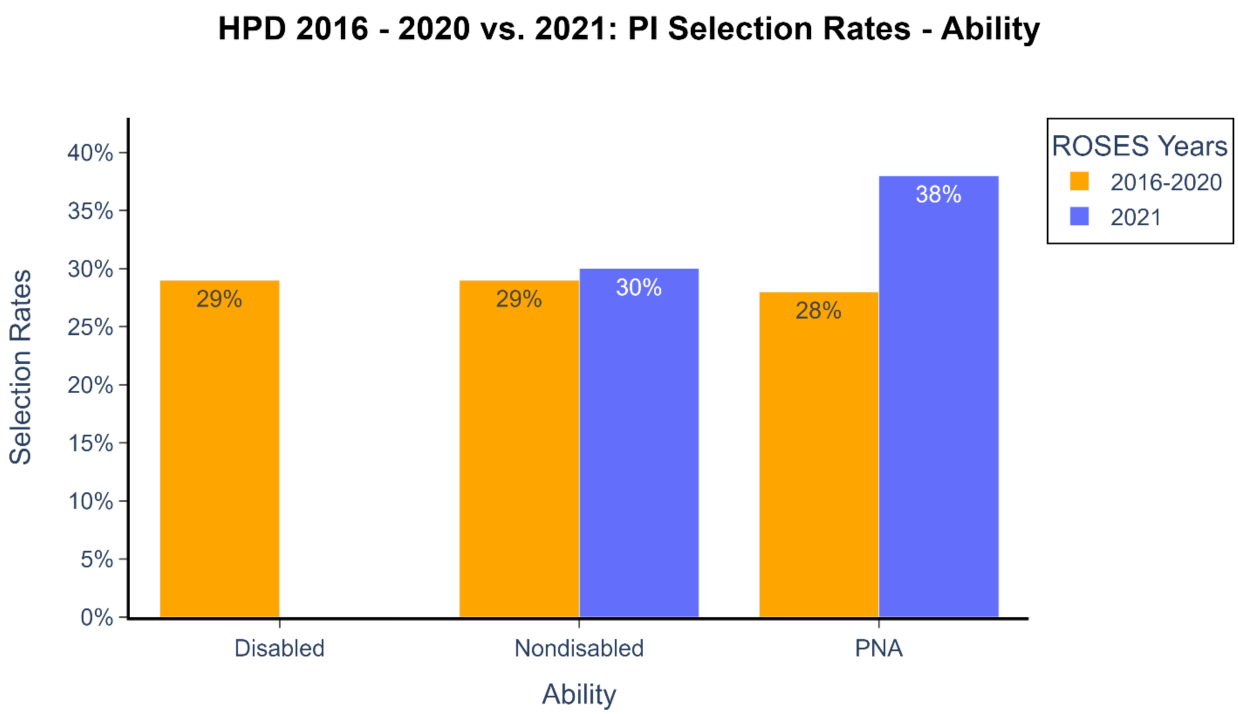
HPD PIs: Selected Ability - Data Table

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

Ability	HPD 2016 - 2020	HPD 2021
Disabled	3%	NR
Nondisabled	77%	76%
PNA	20%	20%

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

HPD 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.

HPD PIs: Ability Selection Rate - Data Table

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

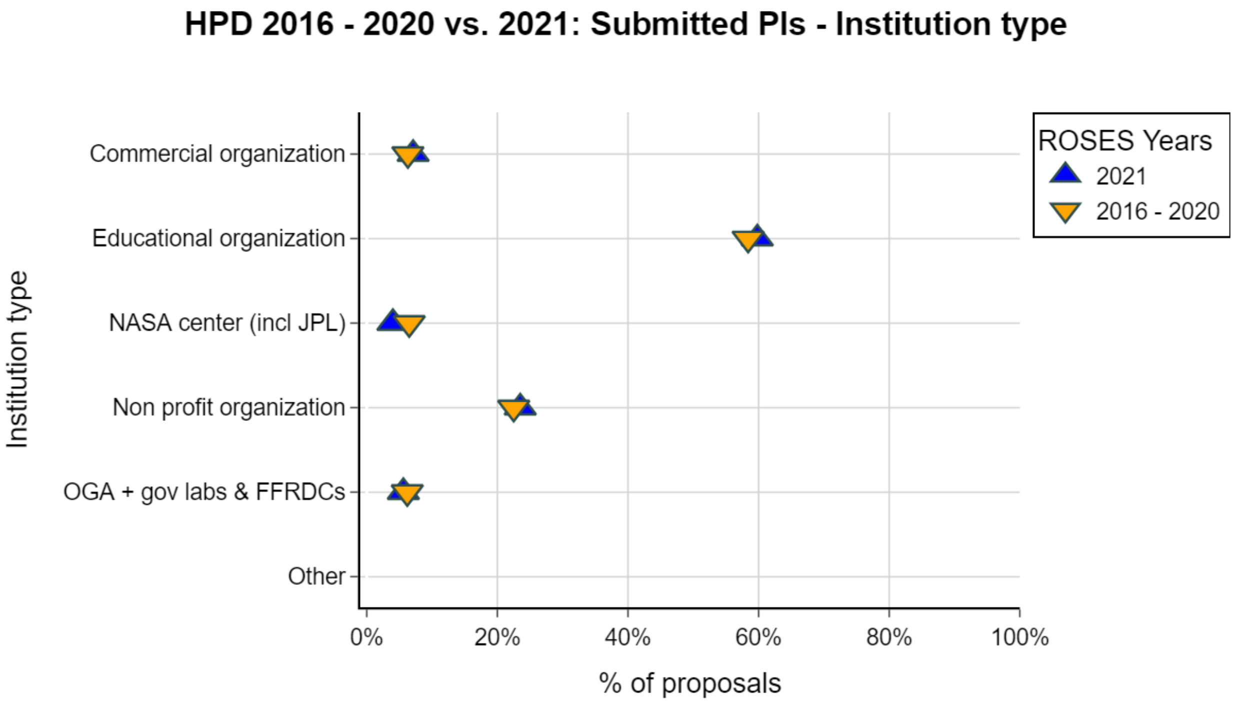
Ability	HPD 2016-2020	HPD 2016-2020 Response/All Abilities	HPD 2021	HPD 2021 Response/All Abilities
Disabled	29%	1	NR	NR
Nondisabled	29%	1	30%	0.94
PNA	28%	0.97	38%	1.19
All Abilities	29%	1	32%	1

Disabled includes hearing, visual, mobility/orthopedic, and other impairment | PNA: Prefer not to answer | NR: Non 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

7.a.i.8. Institutional Analysis

7.a.i.8.a. Institution Type– HPD PIs

HPD 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.

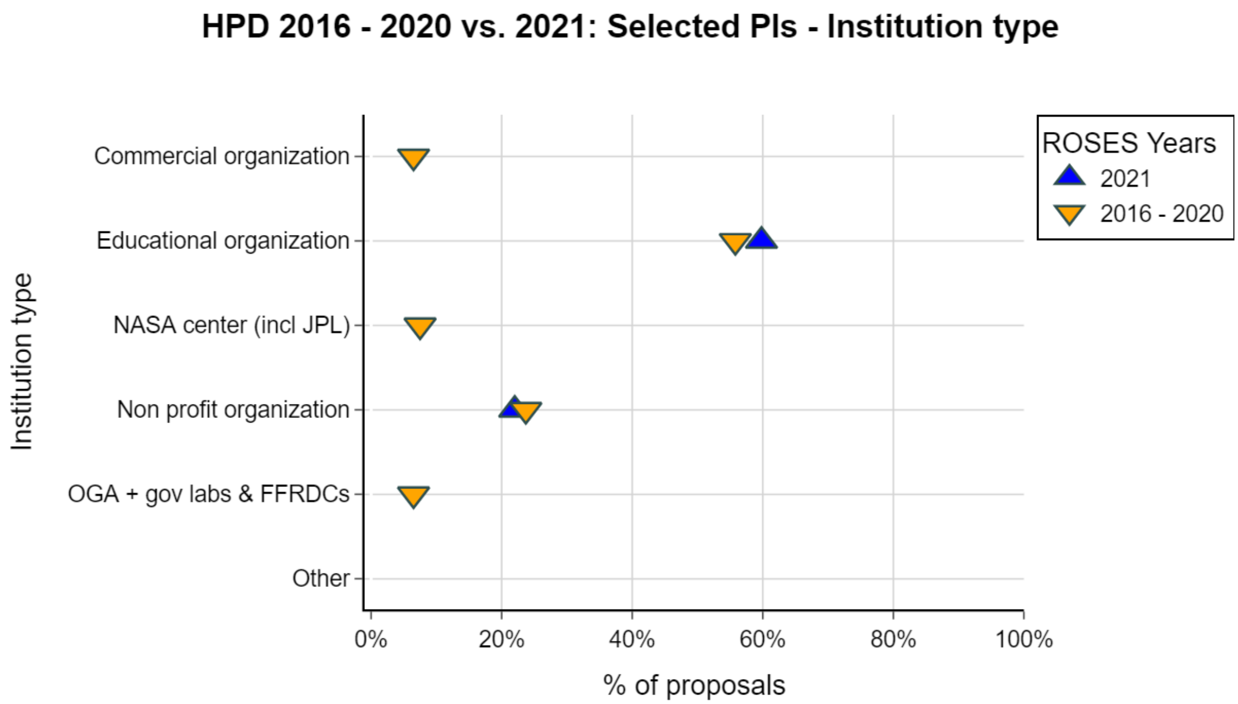
HPD PIs: Submitted Institution Type - Data Table

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

Institution type	HPD 2016 - 2020	HPD 2021
Commercial organization	6%	7%
Educational organization	58%	60%
NASA center (incl JPL)	6%	4%
Non profit organization	22%	24%
OGA + gov labs & FFRDCs	6%	6%
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: Non reportable | ROSES 2016-2020 proposal data are aggregated.

HPD 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), NASA center (incl JPL) (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.

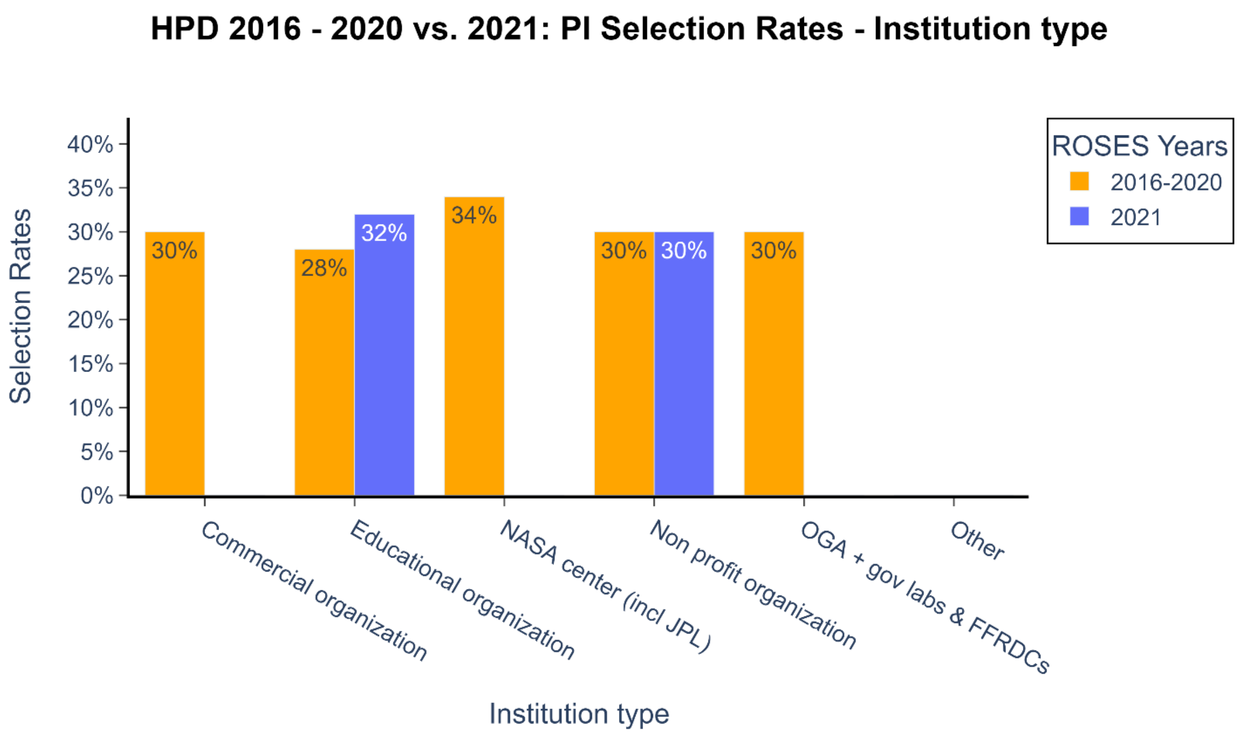
HPD PIs: Selected Institution Type - Data Table

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

Institution type	HPD 2016 - 2020	HPD 2021
Commercial organization	6%	NR
Educational organization	56%	60%
NASA center (incl JPL)	8%	NR
Non profit organization	24%	22%
OGA + gov labs & FFRDCs	6%	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: Non reportable | ROSES 2016-2020 proposal data are aggregated.

HPD 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), NASA center (incl JPL) (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.

HPD PIs: Institution Type Selection Rate - Data Table

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

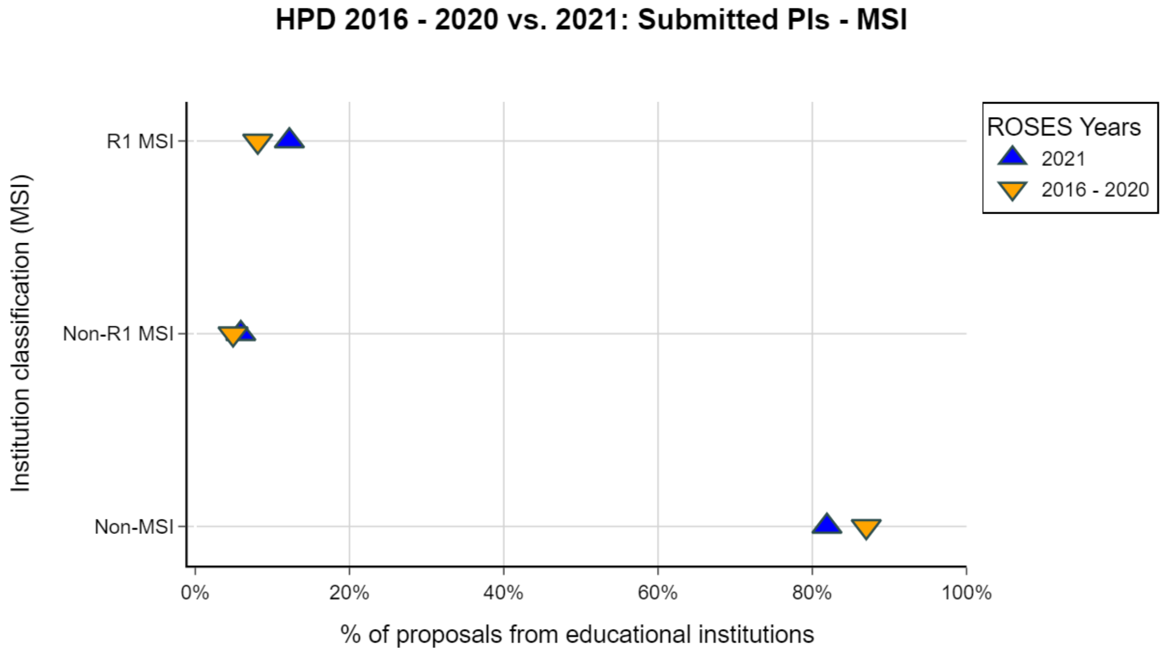
Institution type	HPD 2016-2020	HPD 2016-2020 Response/All Institution types	HPD 2021	HPD 2021 Response/All Institution types
Commercial organization	30%	1.03	NR	NR
Educational organization	28%	0.97	32%	1
NASA center (incl JPL)	34%	1.17	NR	NR
Non profit organization	30%	1.03	30%	0.94
OGA + gov labs & FFRDCs	30%	1.03	NR	NR
Other	NR	NR	NR	NR
All Institution types	29%	1	32%	1

OGA: Other Government Agency | FFRDCs: Federally Funded Research and Development Centers | Other: State, Local or Federally Recognized Tribal Government Agency & Unaffiliated Individuals | NR: Non 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

7.a.i.8.b. Minority Serving Institutions (MSIs) – HPD PIs

HPD Ps: Submitted MSI - Plot



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

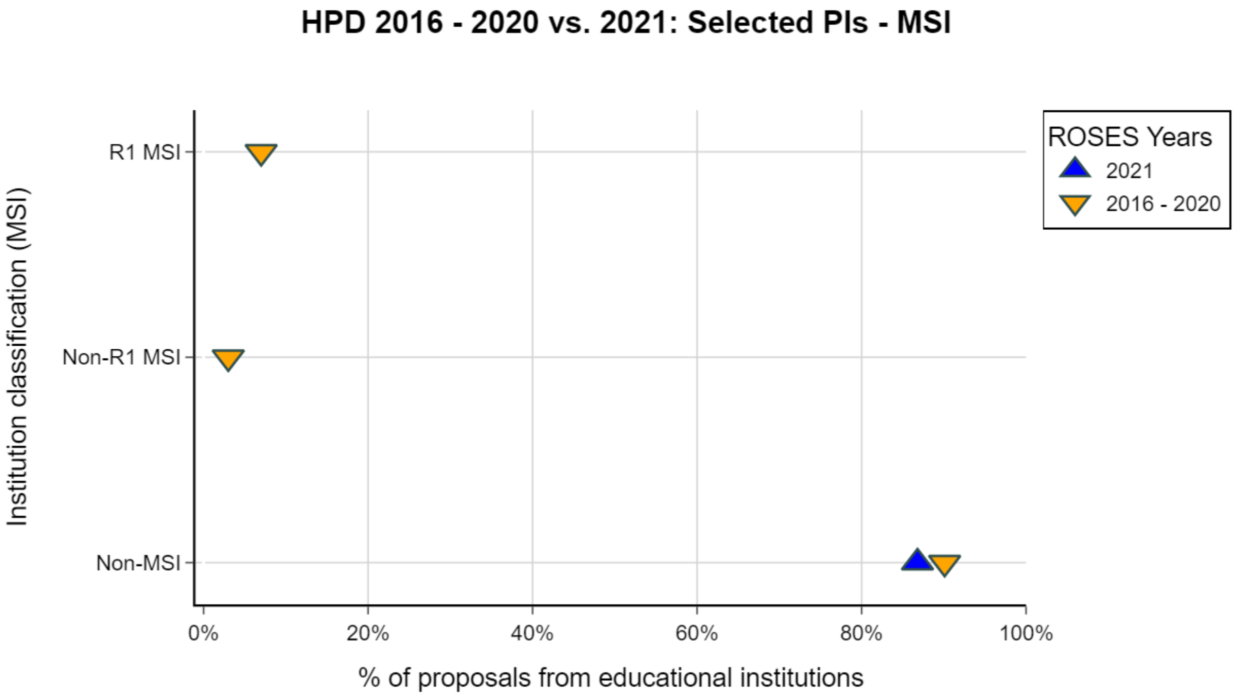
HPD PIs: Submitted MSI - Data Table

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

MSI	HPD 2016 - 2020	HPD 2021
R1 MSI	8%	12%
Non-R1 MSI	5%	6%
Non-MSI	87%	82%

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

HPD PIs: Selected MSI - Plot



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

Suppression categories: R1 MSI (ROSES 2021), 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.

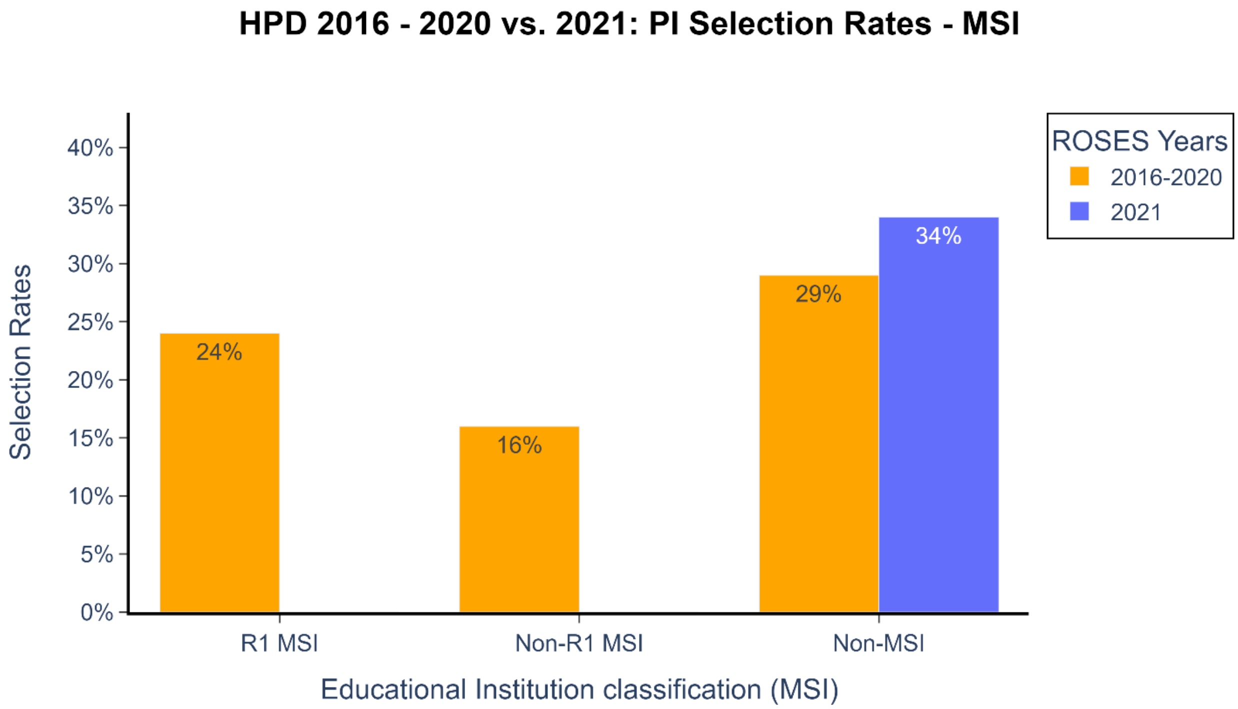
HPD PIs: Selected MSI - Data Table

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

MSI	HPD 2016 - 2020	HPD 2021
R1 MSI	7%	NR
Non-R1 MSI	3%	NR
Non-MSI	90%	87%

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

HPD 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: R1 MSI (ROSES 2021), 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.

HPD PIs: MSI Selection Rate - Data Table

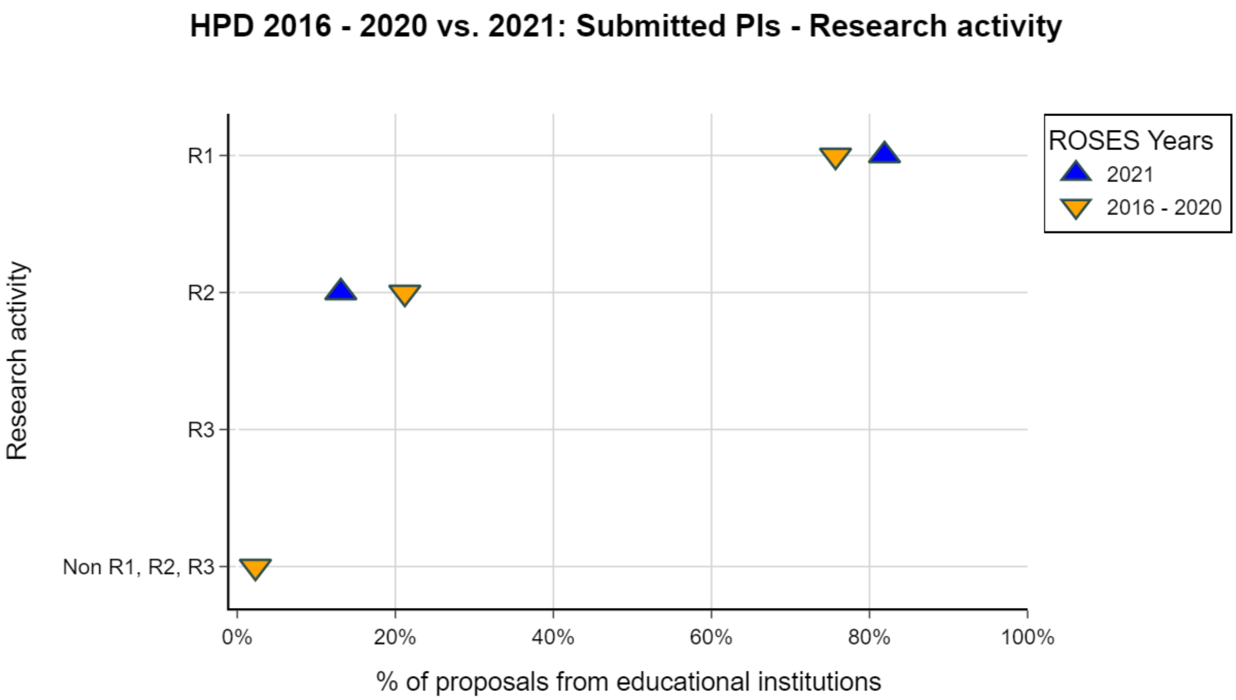
HPD 2016 - 2020 vs. 2021: PI Selection Rates - MSI

MSI	HPD 2016-2020	HPD 2016-2020 Response/All Educational Institutions	HPD 2021	HPD 2021 Response/All Educational Institutions
R1 MSI	24%	0.86	NR	NR
Non-R1 MSI	16%	0.57	NR	NR
Non-MSI	29%	1.04	34%	1.06
All Educational Institutions	28%	1	32%	1

MSI: Minority Serving Institution | R1: Doctoral university - Very high research activity | NR: Non 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

7.a.i.8.c. Carnegie Classification Research Activity – HPD PIs

HPD 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 (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.

HPD PIs: Submitted Research Activity - Data Table

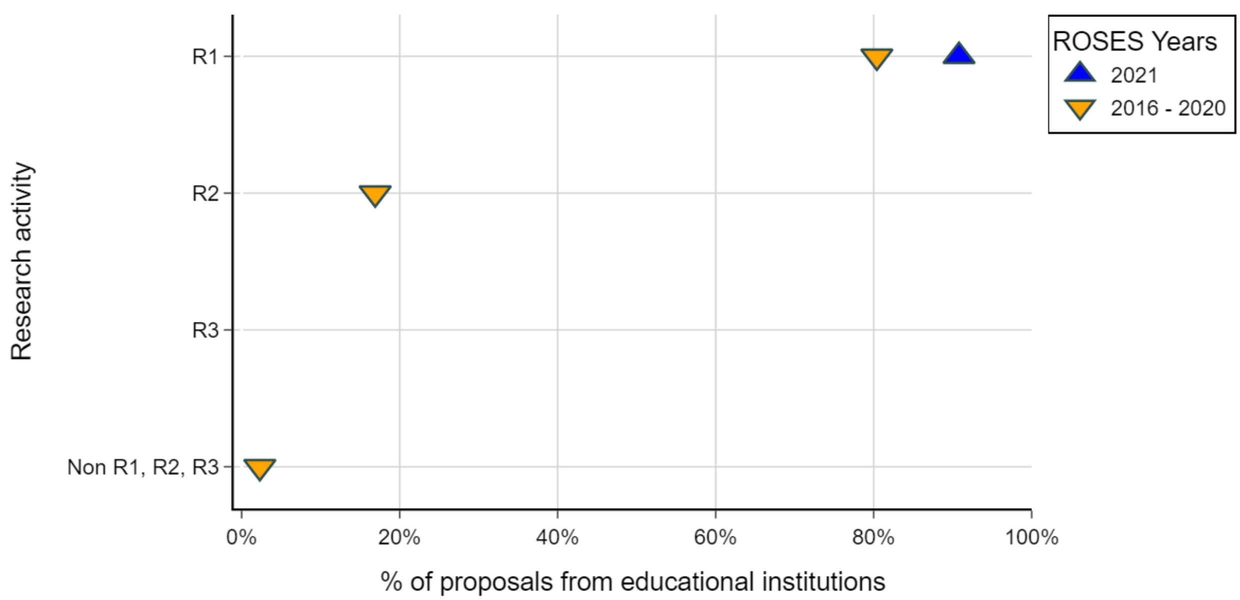
HPD 2016 - 2020 vs. 2021: Submitted PIs - Research activity

Research activity	HPD 2016 - 2020	HPD 2021
R1	76%	82%
R2	21%	13%
R3	NR	NR
Non R1, R2, R3	2%	NR

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

HPD PIs: Selected Research Activity - Plot

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



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: R2 (ROSES 2021), 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.

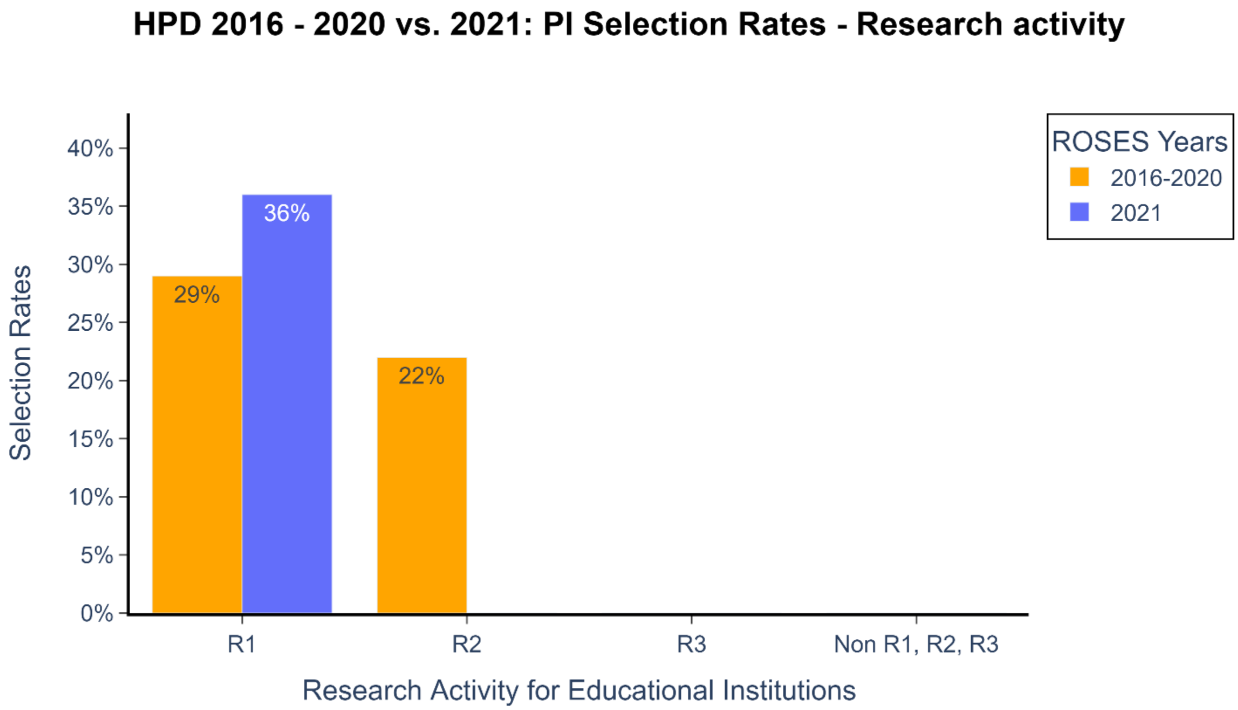
HPD PIs: Selected Research Activity - Data Table

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

Research activity	HPD 2016 - 2020	HPD 2021
R1	80%	91%
R2	17%	NR
R3	NR	NR
Non R1, R2, R3	2%	NR

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

HPD 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: R2 (ROSES 2021), R3 (All years), Non R1, R2, R3 (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.

HPD PIs: Research Activity Selection Rate - Data Table

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

Research activity	HPD 2016-2020	HPD 2016-2020 Response/All Educational Institutions	HPD 2021	HPD 2021 Response/All Educational Institutions
R1	29%	1.04	36%	1.12
R2	22%	0.79	NR	NR
R3	NR	NR	NR	NR
Non R1, R2, R3	NR	NR	NR	NR
All Educational Institutions	28%	1	32%	1

R1: Doctoral university - Very high research activity | R2: Doctoral university - High research activity | R3: Doctoral/professional university | NR: Non 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

7.a.ii. Science Team

7.a.ii.1. Limitations of the data – HPD Science team

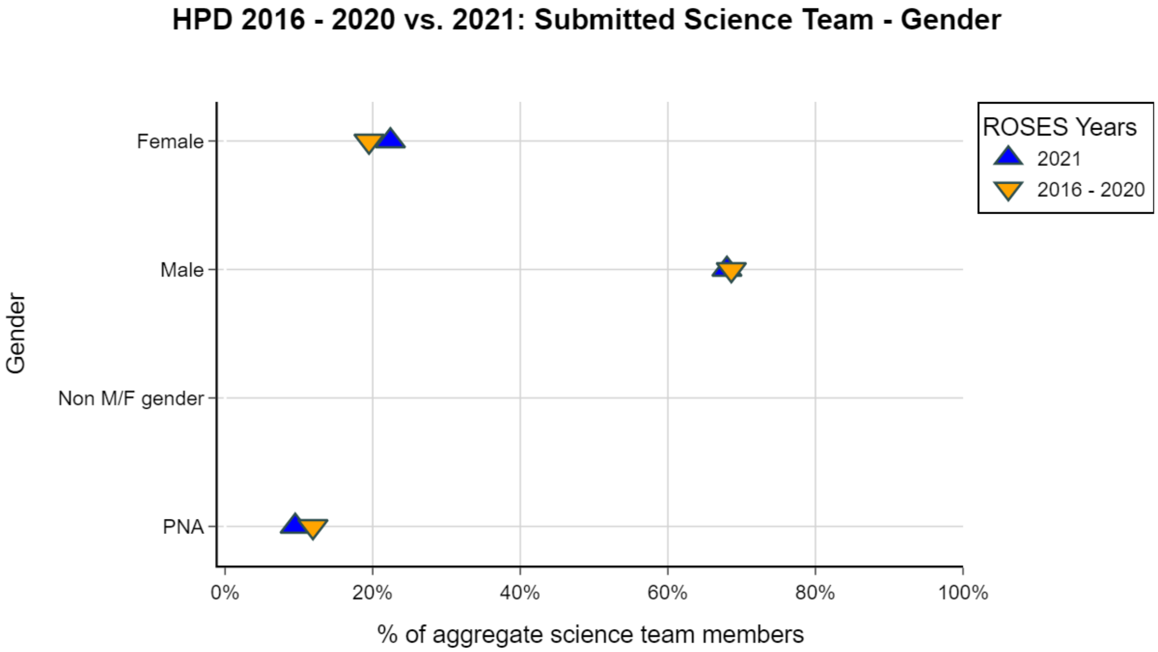
26,043 submitted proposals are included in the ROSES 2016-2021 database. Please see Appendix Table 1 to see which programs are included. The total number of proposals submitted and selected for each ROSES year and the total number of proposals submitted to each SMD Division cannot be reported due to 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 Heliophysics Division, there are ~3,300 submitted proposals over all ROSES years: ~2,900 for ROSES 2016-2020 and ~400 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 proposals: HPD 2016 - 2020: 10% | HPD 2021: 8%
- Selected proposals: HPD 2016 - 2020: 10% | HPD 2021: 9%

7.a.ii.2. Gender - HPD Science Team

HPD 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.

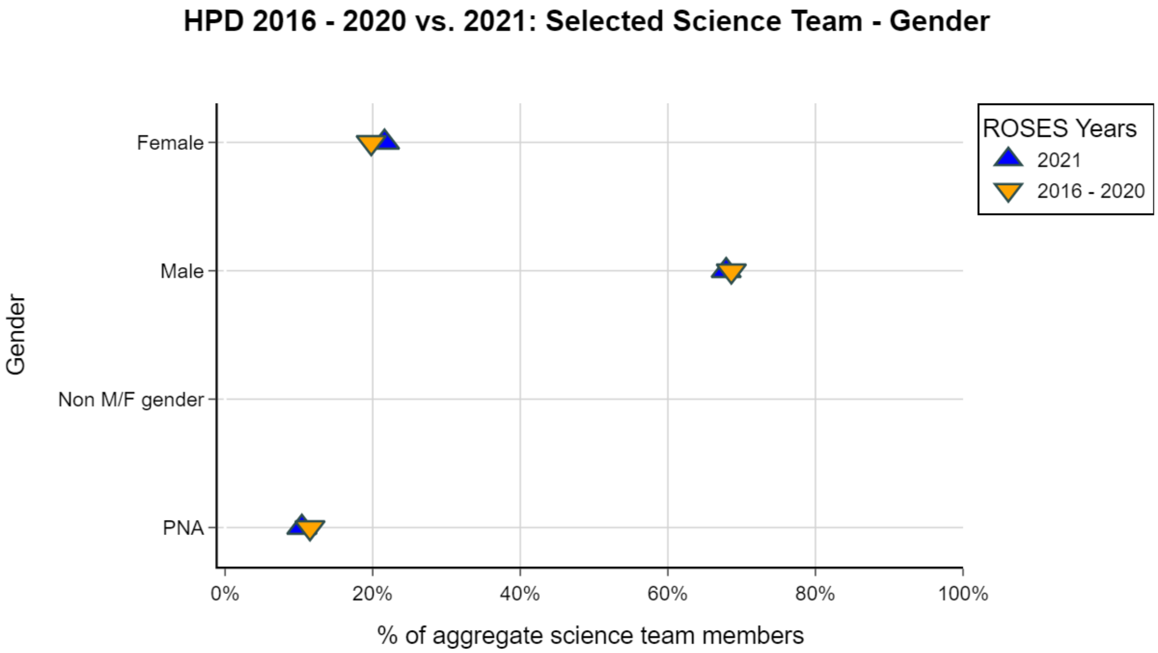
HPD Science Team: Submitted Gender - Data Table

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

Gender	HPD 2016 - 2020	HPD 2021
Female	20%	22%
Male	69%	68%
Non M/F gender	NR	NR
PNA	12%	10%

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

HPD 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.

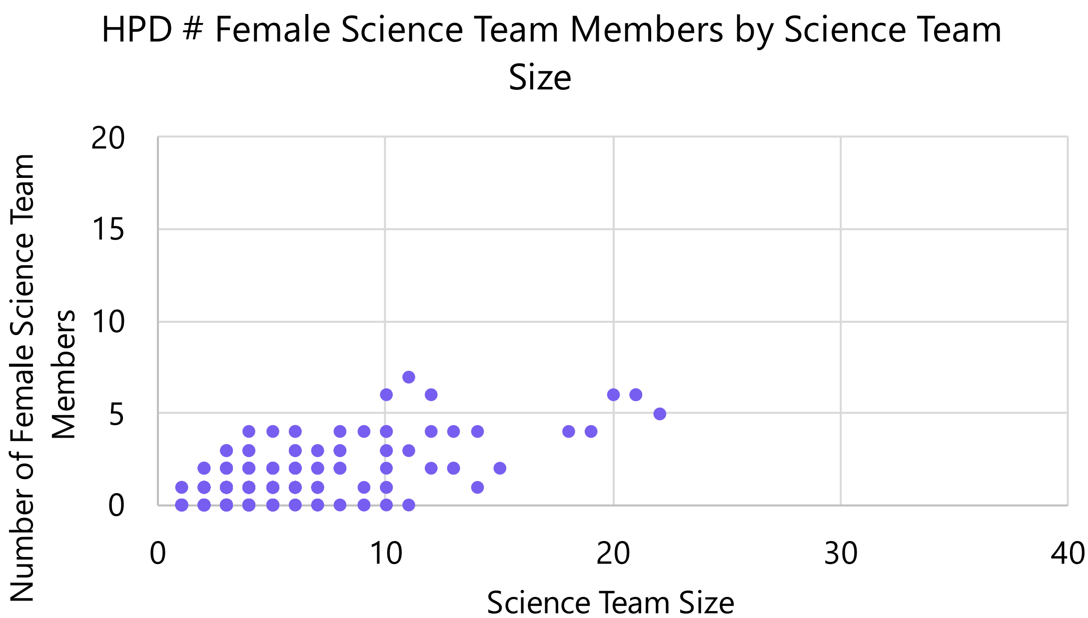
HPD Science Team: Selected Gender - Data Table

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

Gender	HPD 2016 - 2020	HPD 2021
Female	20%	22%
Male	69%	68%
Non M/F gender	NR	NR
PNA	12%	10%

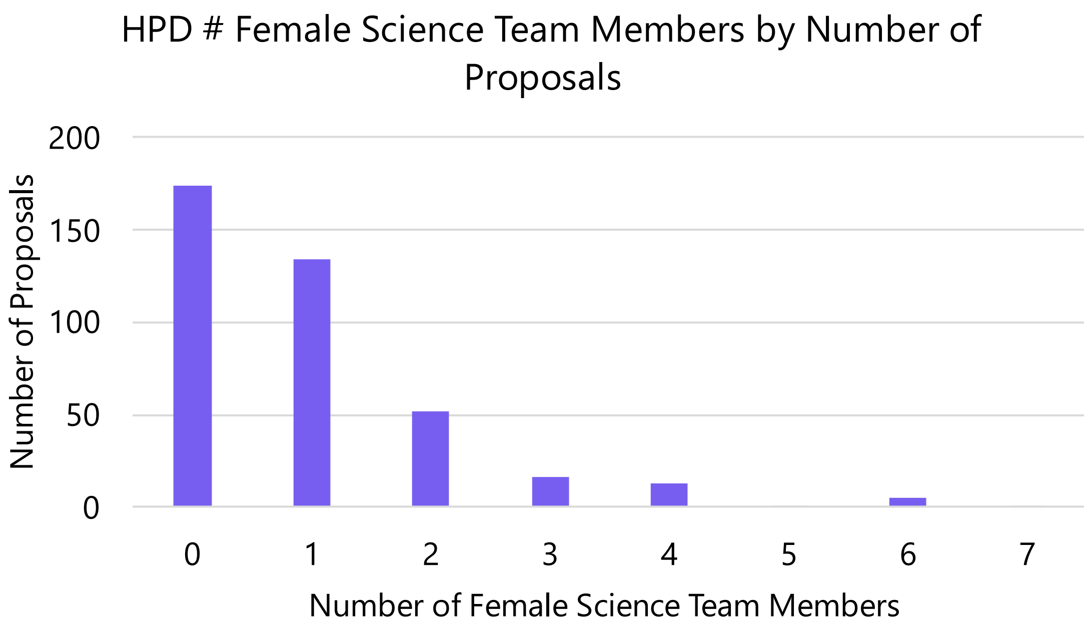
PNA: Prefer not to answer | NR: Non reportable | ROSES 2016-2020 proposal data are aggregated.

HPD ROSES 2021 Science Teams: Female Science Team Members by Science Team Size – Scatter Plot



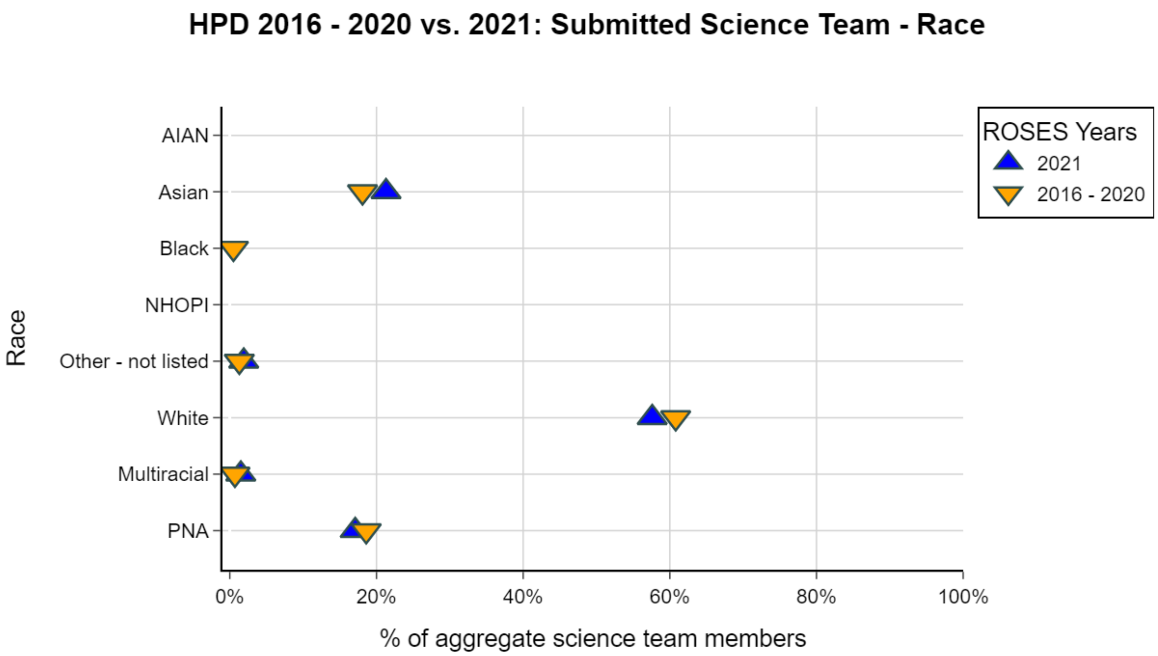
Note: 44% of proposals submitted to ROSES 2021 Heliophysics programs did not include female researchers in their science team. 7% of proposals submitted to ROSES 2021 Heliophysics programs only included the PI as the science team.

HPD ROSES 2021 Science Teams: Female Science Team Members by Number of Proposals - Bar Chart



7.a.ii.3. Race - HPD Science Team

HPD 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 (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.

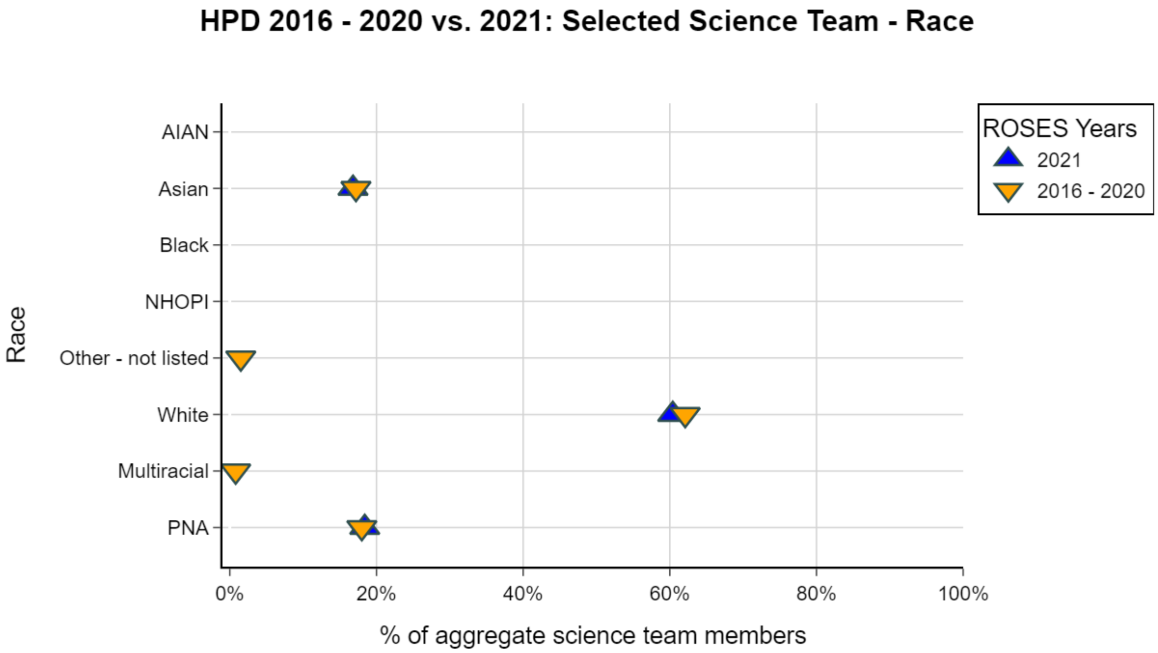
HPD Science Team: Submitted Race - Data Table

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

Race	HPD 2016 - 2020	HPD 2021
AIAN	NR	NR
Asian	18%	21%
Black	< 1%	NR
NHOPI	NR	NR
Other - not listed	1%	2%
White	61%	58%
Multiracial	< 1%	2%
PNA	19%	17%

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

HPD 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 (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.

HPD Science Team: Selected Race - Data Table

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

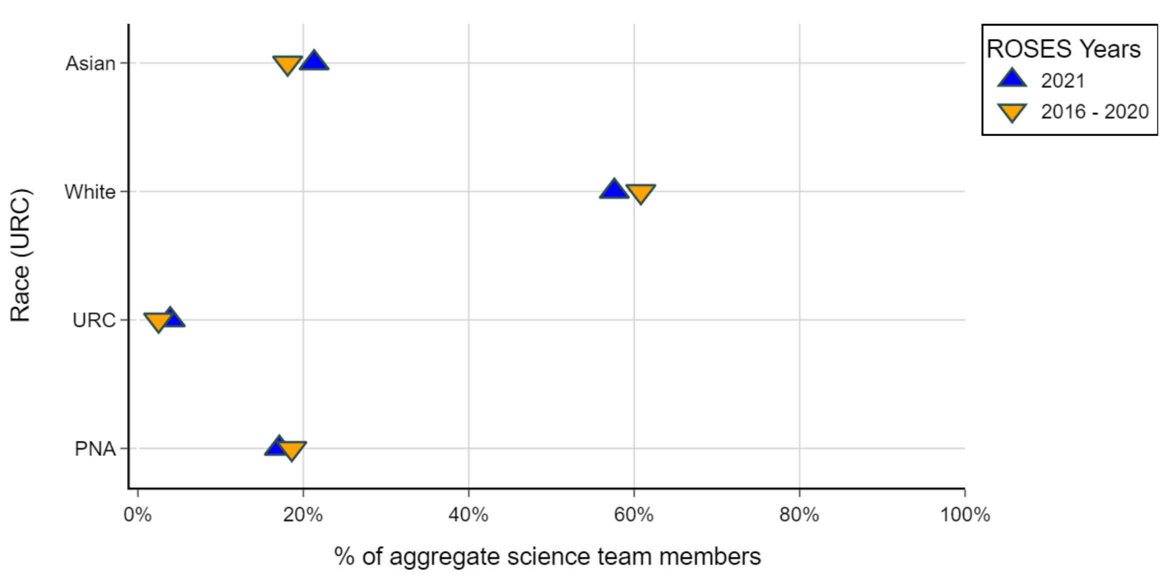
Race	HPD 2016 - 2020	HPD 2021
AIAN	NR	NR
Asian	17%	17%
Black	NR	NR
NHOPI	NR	NR
Other - not listed	2%	NR
White	62%	60%
Multiracial	< 1%	NR
PNA	18%	18%

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

7.a.ii.4. Race using Under-Represented Community (URC) - HPD Science Team

HPD Science Team: Submitted Race (URC) - Plot

HPD 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.

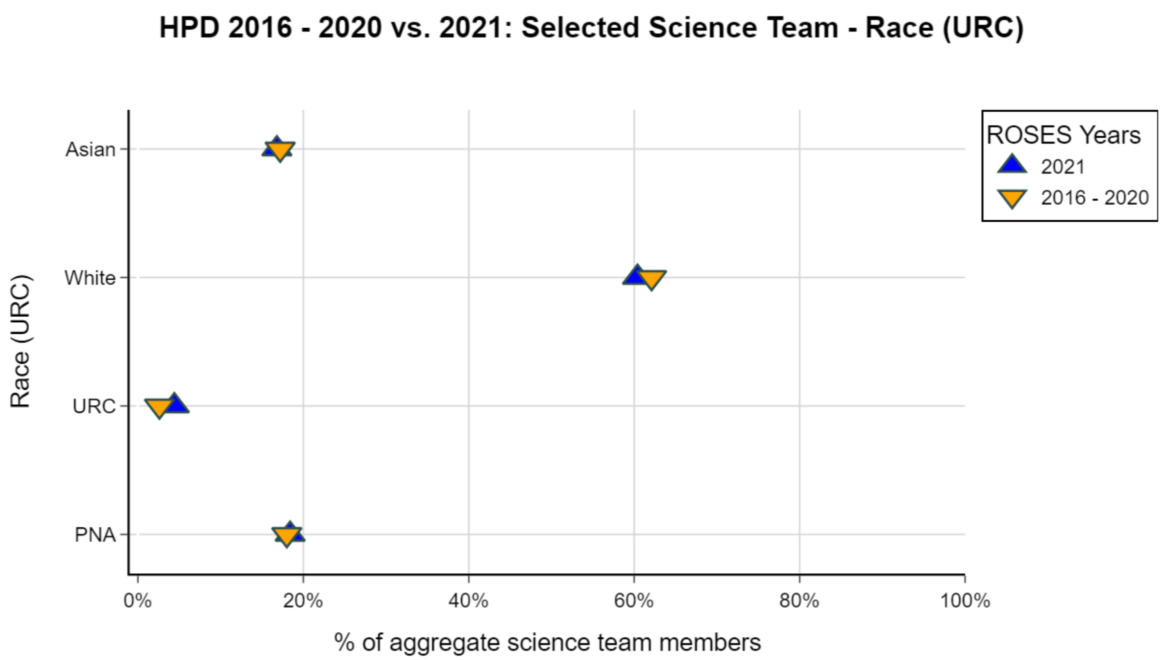
HPD Science Team: Submitted Race (URC) - Data Table

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

Race (URC)	HPD 2016 - 2020	HPD 2021
Asian	18%	21%
White	61%	58%
URC	2%	4%
PNA	19%	17%

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

HPD 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.

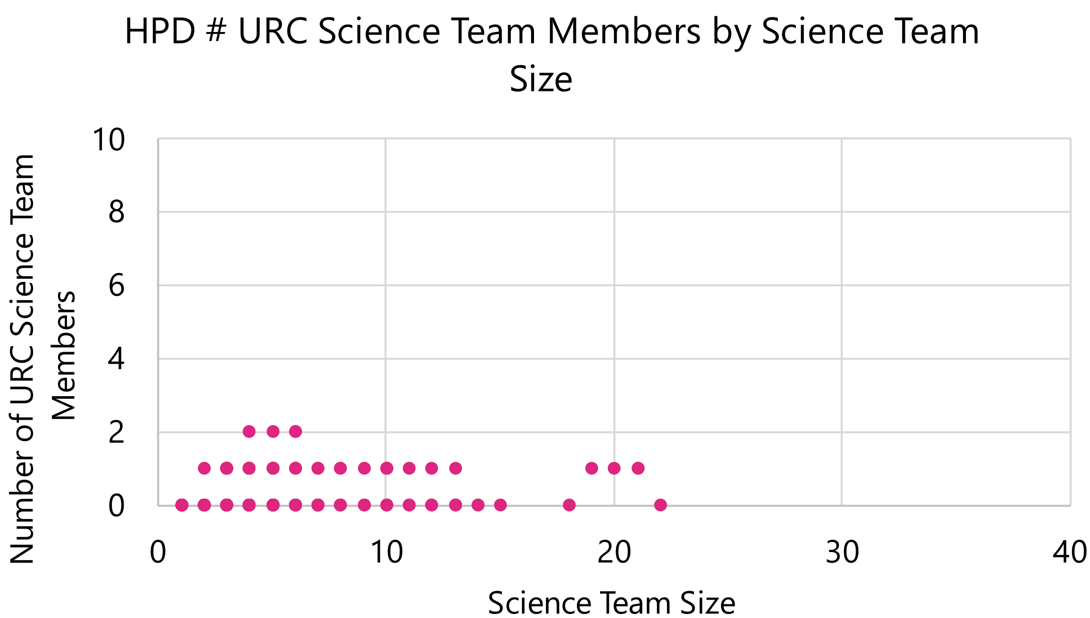
HPD Science Team: Selected Race (URC) - Data Table

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

Race (URC)	HPD 2016 - 2020	HPD 2021
Asian	17%	17%
White	62%	60%
URC	3%	4%
PNA	18%	18%

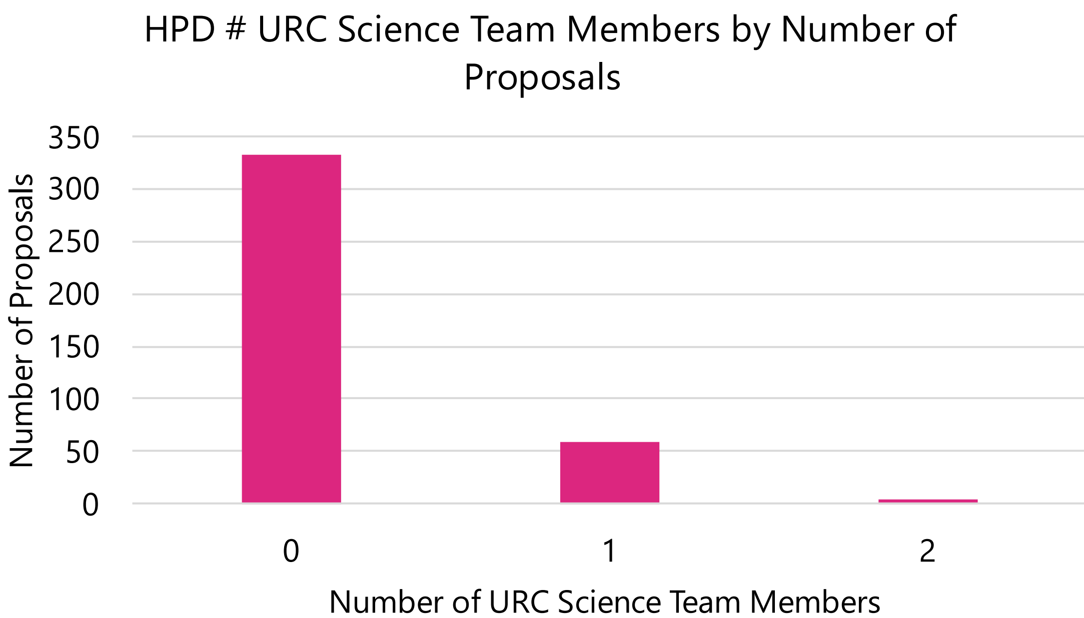
Under-Represented Community (URC) includes American Indian & Alaska Native, Black, Native Hawaiian & Other Pacific Islander, Multiracial, and Other. | PNA: Prefer not to answer | NR: Non reportable | ROSES 2016-2020 proposal data are aggregated.

HPD ROSES 2021 Science Teams: 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 Heliophysics programs did not include URC researchers in their science team. 7% of proposals submitted to ROSES 2021 Heliophysics programs only included the PI as the science team.

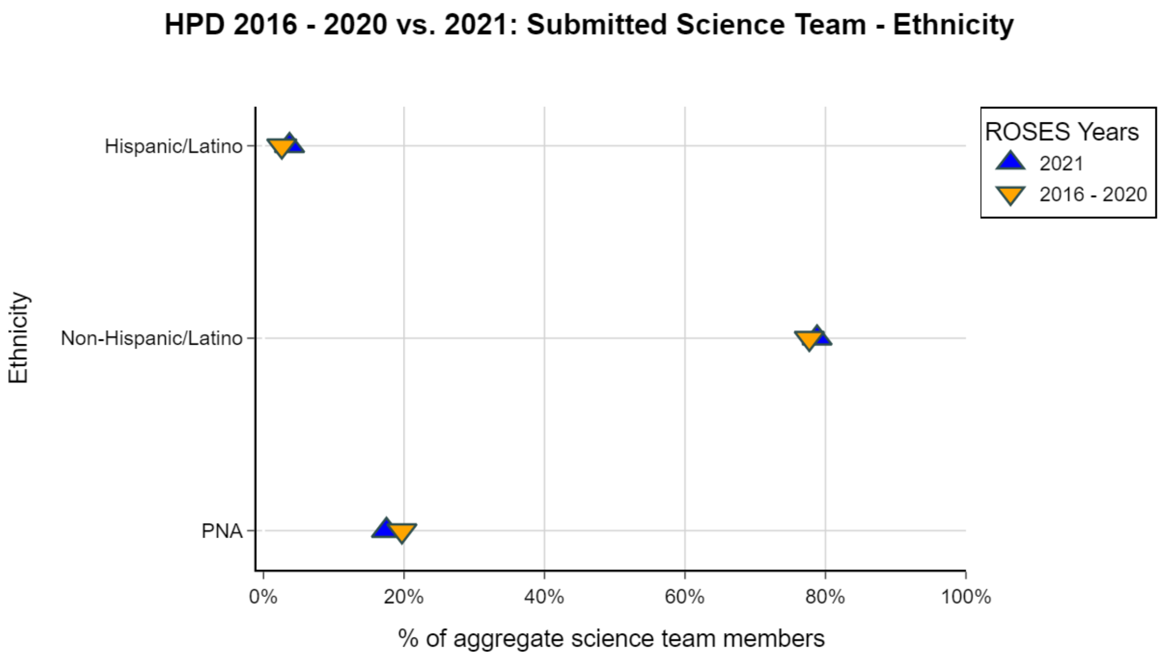
HPD ROSES 2021 Science Teams: URC Science Team Members by Number of Proposals - Bar Chart



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

7.a.ii.5. Ethnicity - HPD Science Team

HPD Science Team: Submitted Ethnicity - Plot



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

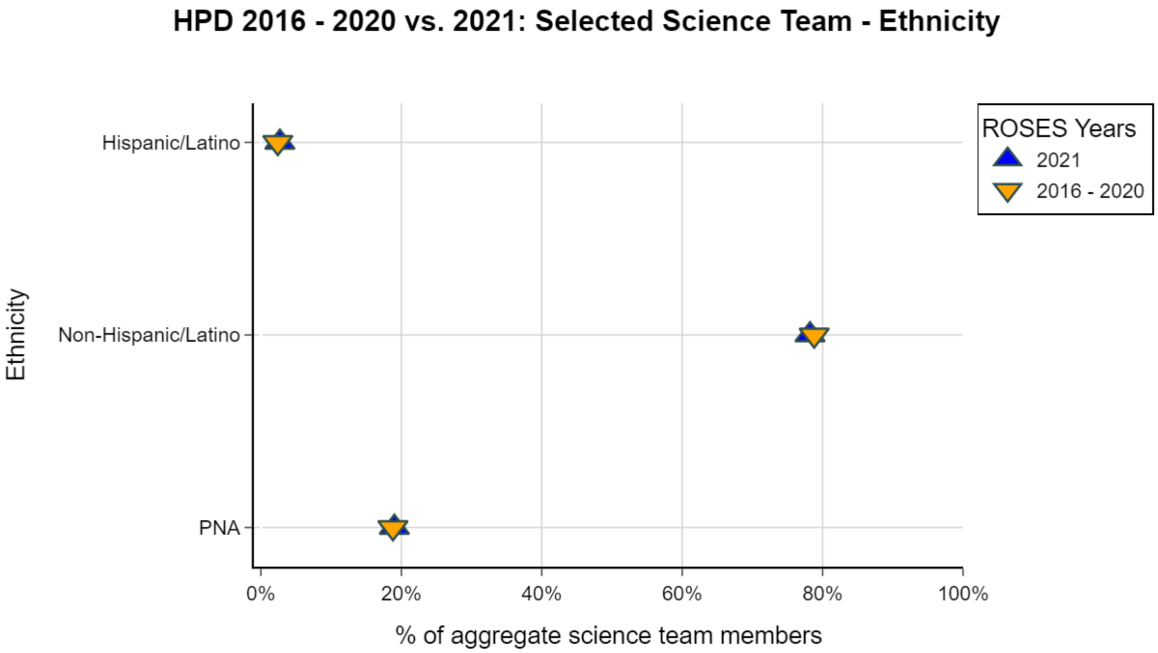
HPD Science Team: Submitted Ethnicity - Data Table

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

Ethnicity	HPD 2016 - 2020	HPD 2021
Hispanic/Latino	3%	4%
Non-Hispanic/Latino	78%	79%
PNA	20%	18%

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

HPD Science Team: Selected Ethnicity - Plot



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

HPD Science Team: Selected Ethnicity - Data Table

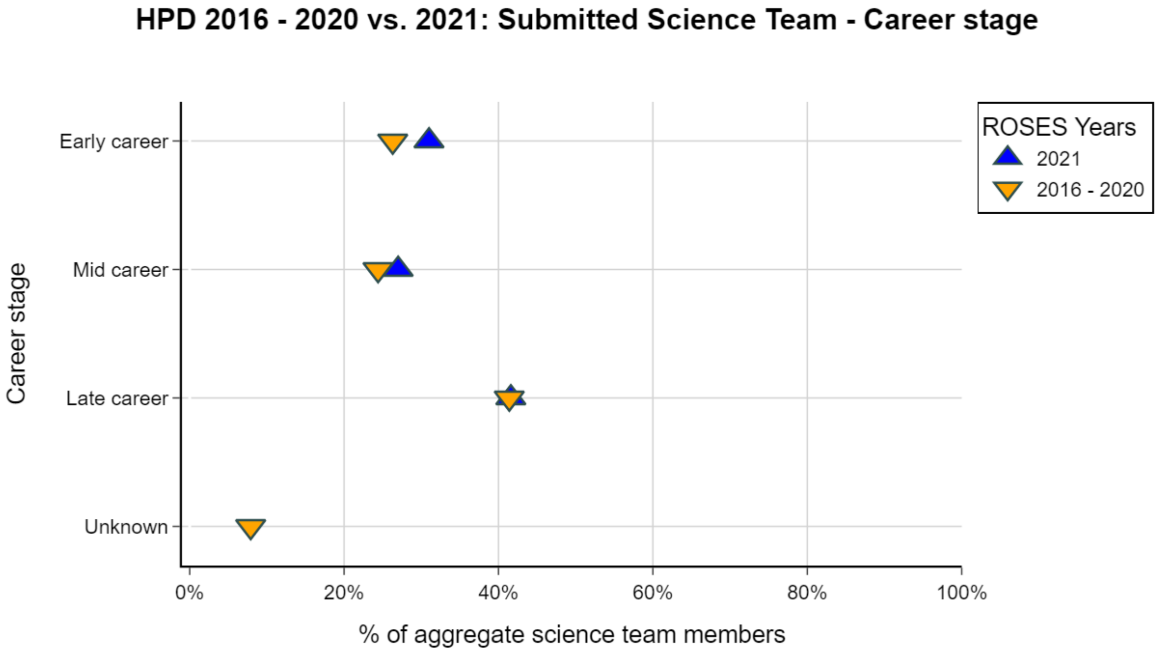
HPD 2016 - 2020 vs. 2021: Selected Science Team - Ethnicity

Ethnicity	HPD 2016 - 2020	HPD 2021
Hispanic/Latino	2%	3%
Non-Hispanic/Latino	79%	78%
PNA	19%	19%

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

7.a.ii.6. Career Stage – HPD Science Team

HPD 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.

Suppressed 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.

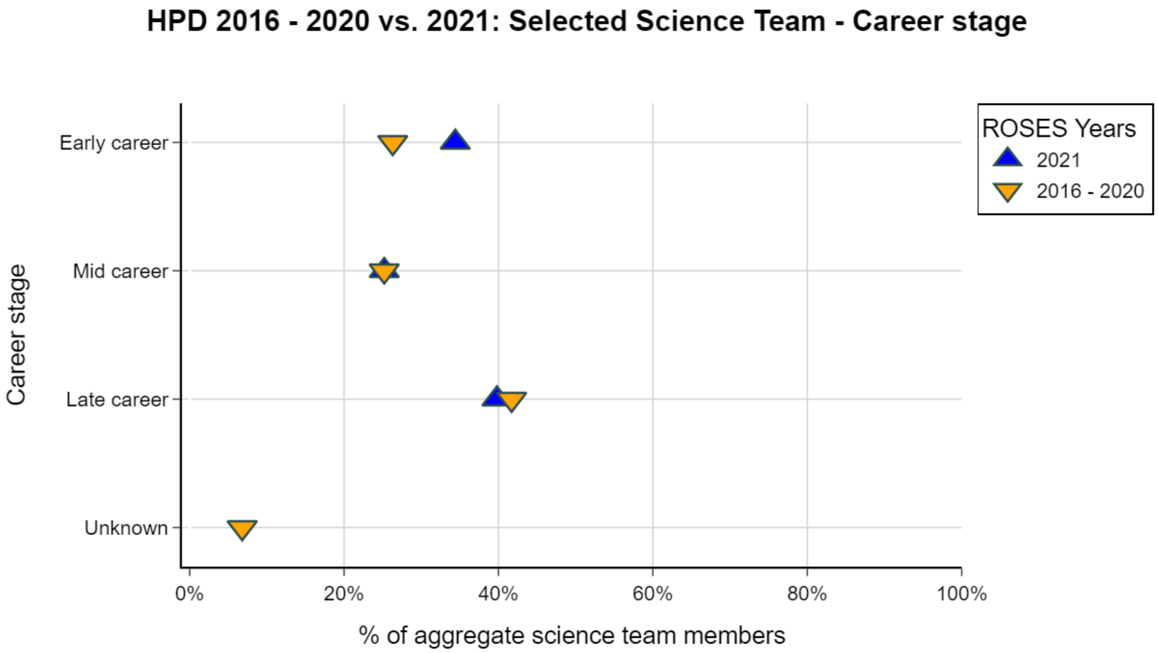
HPD Science Team: Submitted Career Stage - Data Table

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

Career stage	HPD 2016 - 2020	HPD 2021
Early career	26%	31%
Mid career	24%	27%
Late career	41%	42%
Unknown	8%	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: Non reportable | ROSES 2016-2020 proposal data are aggregated.

HPD 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.

Suppressed 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.

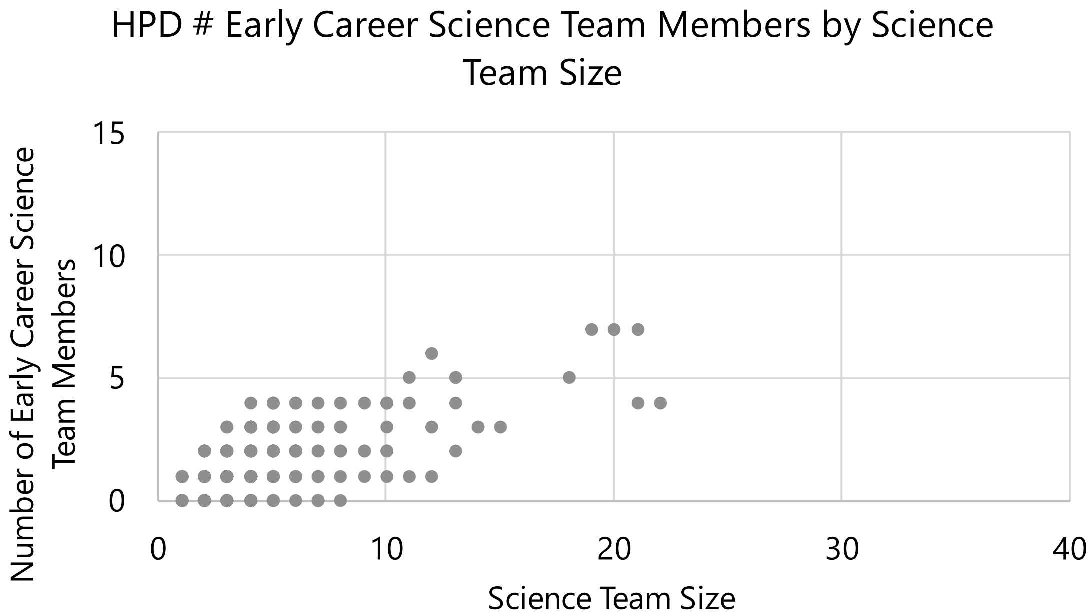
HPD Science Team: Selected Career Stage - Data Table

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

Career stage	HPD 2016 - 2020	HPD 2021
Early career	26%	34%
Mid career	25%	25%
Late career	42%	40%
Unknown	7%	NR

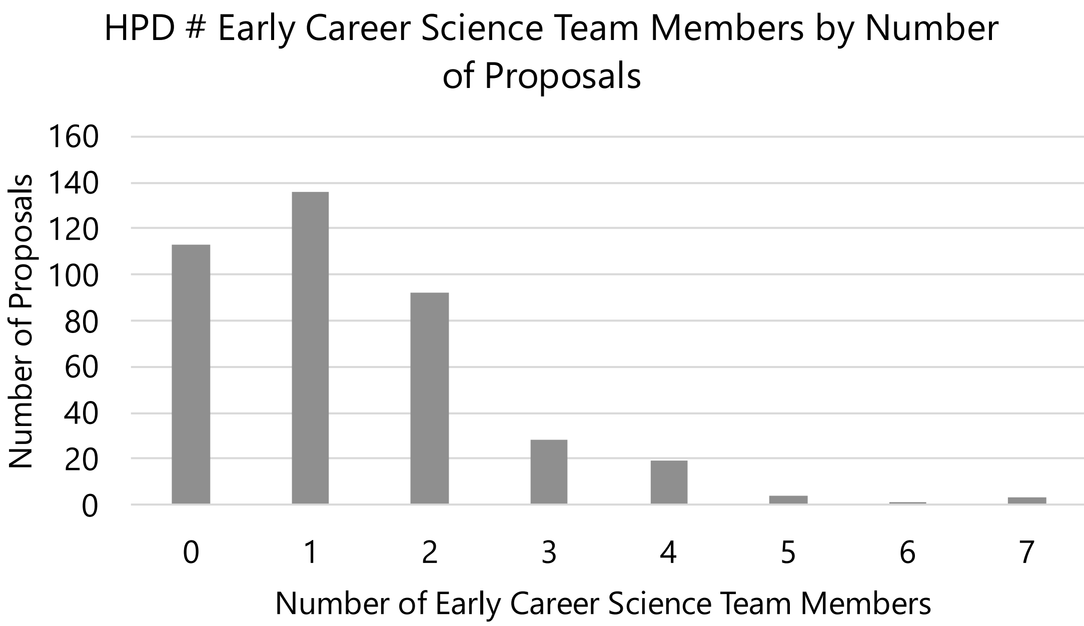
Early career: < 10 years since earning final degree | Mid career: 10 - 19 years since earning final degree | Late career: 20+ years since earning final degree | NR: Non reportable | ROSES 2016-2020 proposal data are aggregated.

HPD ROSES 2021 Science Teams: Early Career Science Team Members by Science Team Size – Scatter Plot



Early career: < 10 years since earning final degree | Note: 29% of proposals submitted to ROSES 2021 Heliophysics programs did not include early career researchers in their science team. 7% of proposals submitted to ROSES 2021 Heliophysics programs only included the PI as the science team.

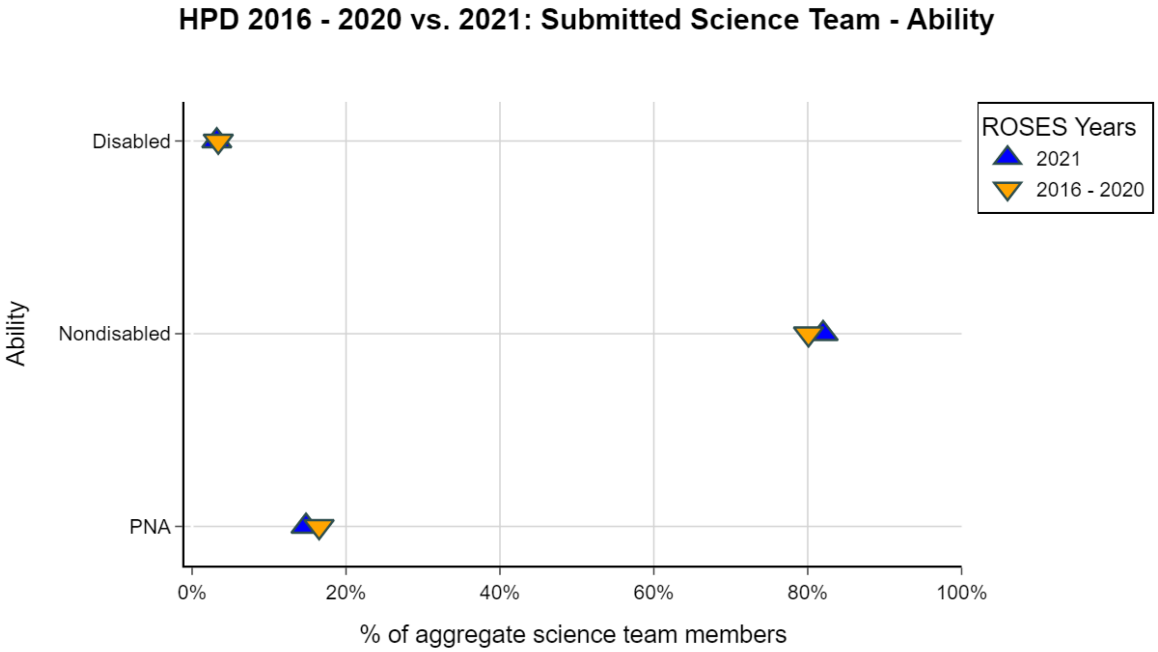
HPD ROSES 2021 Science Teams: Early Career Science Team Members by Number of Proposals - Bar Chart



Early career: < 10 years since earning final degree

7.a.ii.7. Disability Status - HPD Science Team

HPD 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.

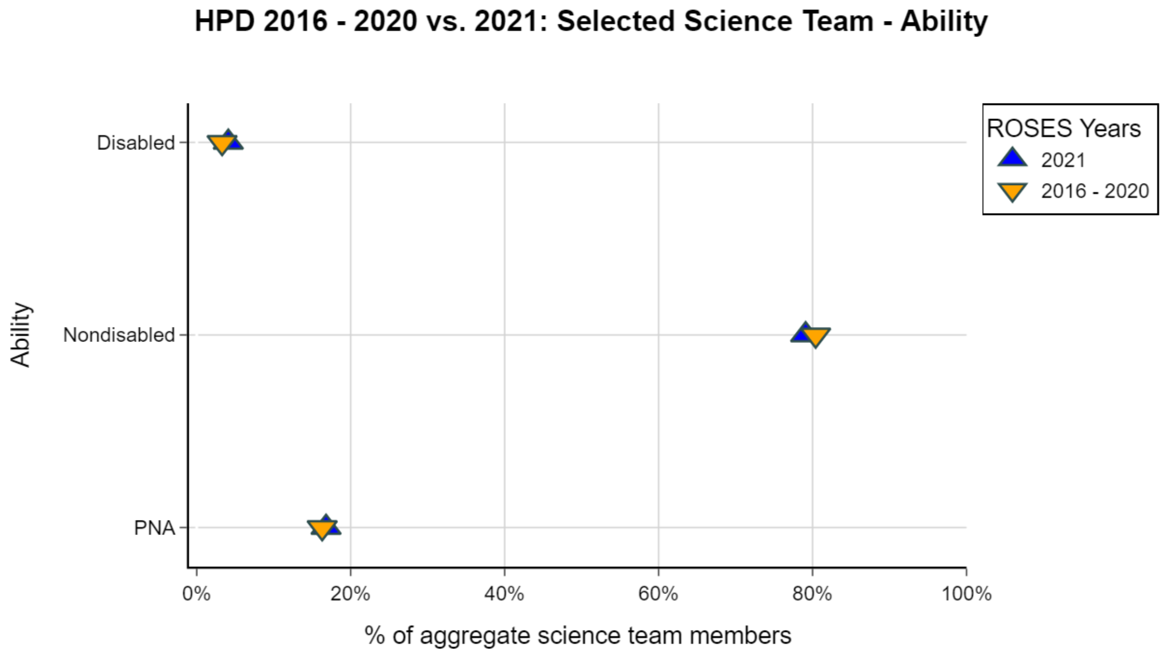
HPD Science Team: Submitted Ability - Data Table

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

Ability	HPD 2016 - 2020	HPD 2021
Disabled	3%	3%
Nondisabled	80%	82%
PNA	16%	15%

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

HPD 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.

HPD Science Team: Selected Ability - Data Table

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

Ability	HPD 2016 - 2020	HPD 2021
Disabled	3%	4%
Nondisabled	80%	79%
PNA	16%	17%

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

7.b. Proposal Data

7.b.i. New PI

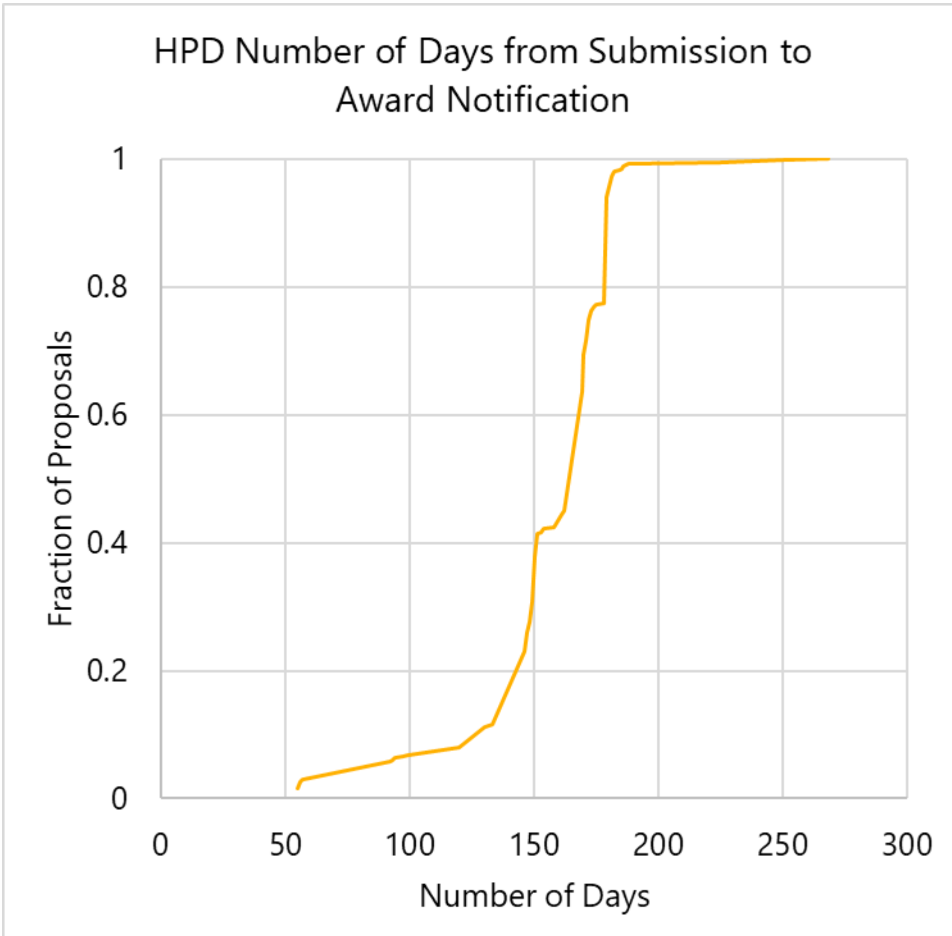
Comparison of Proposal Statistics of New PIs and Unique PIs for ROSES 2021

HPD 2021	New PIs	Unique PIs	New PI %
Selected	43	119	36%
Submitted	145	315	46%
Selection Rate	30%	38%	

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.

7.b.ii. Time from Proposal Submission to Award Notification for ROSES 2021

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



Note: Number of days from proposal submission to 80% of award notifications for HPD is 179 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."

7.c. ROSES 2021 Selection Announcements

Appendix B. Heliophysics Division

Appendix	Program Element Name
B.2	Heliophysics Supporting Research
B.4	Heliophysics Guest Investigator Open
B.5	Living With a Star Science
B.6	Living With a Star Strategic Capabilities
B.7	Space Weather Science Application Research-to-Operations-to-Research
B.8	Heliophysics Technology and Instrument Development for Science
B.9	Heliophysics Low Cost Access to Space
B.10	Heliophysics Flight Opportunities Studies
B.12	Heliophysics Data Environment Enhancements
B.15	Geospace Dynamics Constellation Interdisciplinary Scientists
B.16	Heliophysics Mission Concept Studies
B.17	Interdisciplinary Science for Eclipse
B.18	Living With a Star Tools and Methods
B.19	Heliophysics Innovations for Technology and Science
B.20	Living with a Star Infrastructure

Heliophysics Supporting Research
Abstracts of selected proposals
NNH21ZDA001N-HSR

Below are the abstracts of proposals selected for funding for the HSR Heliophysics Supporting Research (PI) name, institution, and proposal title are also included. 112 proposals were received in response to this opportunity. On July 1, 2022, 20 proposals were selected for funding. On September 12, 2022, 4 additional proposals were selected.

William Abbett/University of California, Berkeley
Magnetic Flux Emergence and Coupling of Scales in Eruptive Configurations from the Upper Convection Zone to the Solar Corona

Goals and Objectives:
We propose to perform large-scale, high-resolution 3D radiative-magnetohydrodynamic simulations along with observational data analyses to better understand the role of magnetic flux emergence through the Sun's visible surface. Our four principle scientific objectives are to: (O1) Determine how the subsurface structure of emerging active-region (AR) scale flux ropes affects resulting surface magnetic structure; (O2) Understand how convective turbulence impacts the structure of AR magnetic fields over multiple scales; (O3) Characterize the formation of non-potential magnetic structures at and near the photosphere; and (O4) Better understand energization of magnetic fields in the corona.

Methodology:
To achieve our objectives, we will analyze AR observations by SDO/HMI & AIA in parallel with output of ab initio, 3D, radiative-MHD models capable of (i) simulating convective turbulence interacting with emerging AR fields in the Sun's upper-convection zone and (ii) including magnetic evolution in the low atmosphere, transition region, and corona. Specifically, we propose the following Tasks that, together, address our scientific objectives: (T1) Study how pre-emergence structure affects surface structure by varying the initial subsurface field configurations in numerical simulations of emerging fields; (T2) Study how magnetic fields evolve in their turbulent environment by analyzing motions of fluxes, Doppler patterns, and development of magnetic shear near polarity inversion lines (PILs) in parallel analyses of simulated and observed datasets; (T3) Study formation of non-potential surface structures, such as sheared PILs, vertical currents, and filament channels, by studying emerging fields' structure (coherence, twist, distribution) and dynamics (collisional shearing, cancellation) in parallel analyses of simulated and observed datasets; and (T4) Study coronal energization from emergence & subsequent evolution, by comparing SDO/AIA and HMI data with our numerical models to better understand development of quantities such as free energy, magnetic helicity, and twist in coronal fields.

Relevance:

This proposal directly addresses the high-level Heliophysics Research Program goal; namely, to "Understand the Sun and its interactions with the Earth and the Solar System…", and also addresses the recommendations of the most recent Heliophysics Decadal Survey, to "Advance our understanding of the Sun's activity, and the connections between solar variability and Earth and planetary space environments…" and to discover and characterize fundamental physical processes that occur from the Sun to the heliosphere. Specifically, this proposal will use theory, numerical modeling, and observational data to better understand physical processes underlying the emergence of magnetic flux over multiple scales, and its impact on the initiation of solar eruptions.

Hassanali Akbari/Catholic University Of America
Determining processes underlying plasma waves and solitary structures associated with planetary ion escape at Mars

NASA's Mars Atmosphere and Volatile EvolutioN (MAVEN) spacecraft has been in orbit around Mars since September 2014. Its continuous measurements in the Martian plasma environment have established the persistence presence of a stream of planetary ions (mainly, O+ and O2+) that originate from the dayside ionosphere and travel outward into deep space. An intriguing feature that is observed along with the escaping ions is the presence of large-amplitude plasma waves and bipolar and unipolar solitary structures. The observations that are unprecedented in many ways provide an excellent opportunity to investigate fundamental plasma processes that take place in plasma environment of unmagnetized bodies. The proposed work will employ a combination of theory and numerical simulations constrained by MAVEN observations to investigate the nature, causes, and effects of the plasma instabilities associated with ion acceleration in the Martian magnetosphere. Specifically, this study will address the following Science Questions:

1. What plasma instabilities are responsible for the generation of the waves observed in conjunction with planetary ion acceleration?
2. What is the nature, cause, and effect of the solitary structures in the turbulence region?
3. How significant are instabilities in the ion acoustic frequency range for transfer of energy and momentum and energization of planetary ions in the interaction region?

While the measurements are obtained at Mars, the processes that will be investigated and the insight that will be produced are universal and apply to various environments, including to the Earth's auroral plasma.

Methodology:
Our methodology relies heavily on theory and numerical simulations that are constrained by MAVEN observations of particles and fields. We will employ linear stability analysis to identify the wave modes and the mechanisms underlying their excitation. We will utilize one- and two-dimensional Vlasov and Particle-in-Cell simulations to study the nonlinear stage of the

instabilities and will investigate the generation of the solitary structures. By incorporating the results of the linear stability analysis and the numerical simulations into extensive analysis of MAVEN data, we will investigate the role of turbulence in the exchange of energy and momentum between the solar wind and planetary plasmas.

Relevance:

The proposed work employs a combination of theory and numerical simulations based on MAVEN observations to investigate 1) the nature of plasma instabilities associated with heavy ion acceleration in the magnetosphere of Mars (and other unmagnetized bodies) and 2) their implications in the context of solar wind interactions with the Martian ionosphere. The proposed work directly addresses NASA's Heliophysics' overarching goal "to understand the Sun and its interactions with the Earth and the Solar System". By investigating the "fundamental plasma wave-particle interactions", mentioned in Appendix B. Heliophysics Research Program, the proposed research addresses the objective "Explore and characterize the physical processes in the space environment from the Sun to the heliopause and throughout the universe". The proposed study primarily employs theory and simulation tasks, making it unsuitable for data analysis programs.

Xin An/University of California, Los Angeles

Energy cascade of low-frequency electromagnetic waves to high-frequency electrostatic waves in the inner heliosphere

The Parker Solar Probe measurements during the first two encounters showed that coherent ion-scale electromagnetic waves are frequently observed in the inner heliosphere. These waves were shown to be fast magnetosonic and Alfven ion-cyclotron waves propagating quasi-parallel to a local magnetic field. These waves are presumably produced by instabilities associated with unstable proton distribution functions, but the most critical question concerns the nonlinear evolution and dissipation of these waves. The Parker Solar Probe measurements have shown that this dissipation is associated with nonlinear coupling of these low-frequency electromagnetic waves to higher frequency electrostatic waves (ion-acoustic waves), which can efficiently interact with electrons. It is currently not known why and how the coupling between the waves occurs, and what key parameters control such coupling process in the inner heliosphere.

The scientific goal of this proposal is to determine the nature and occurrence of the coupling process between low-frequency electromagnetic and high-frequency electrostatic waves in the solar wind. This scientific goal requires us to address the following questions:

1. What are conditions favorable for the coupling between ion-scale electromagnetic waves and high-frequency electrostatic waves in the inner heliosphere?
2. How does the efficiency of the wave coupling process depend on the plasma parameters scaling with the radial distance?
3. What is the nature of the coupling process and what are the key parameters that control the coupling process?

The project methodology combines analysis of Parker Solar Probe (PSP) measurements (spectra and waveforms of electric and magnetic fields provided by the FIELDS instrument suite, particle measurements provided by the SWEAP instrument suite), the theoretical investigations (testing and comparing two candidate theories: [a] nonlinear fluid steepening; [b] kinetic instabilities driven by nonlinear Landau resonant ions), and numerical simulations (1D multi-fluid non-ideal magnetohydrodynamic code and 1D kinetic particle-in-cell code).

By combining theory and numerical simulations, substantiated with and guided by PSP data, this project will provide a comprehensive understanding on the nonlinear dynamics and dissipation of coherent electromagnetic waves in the inner heliosphere. The coupling process is of universal nature and is potentially important for astrophysical and laboratory plasmas. As such, the project is directly relevant to one of the Heliophysics overarching goals or specific objectives, that is to "Explore and characterize the physical processes in the space environment from the Sun to the heliopause and throughout the universe".

Rafael Luiz Araujo de Mesquita /Johns Hopkins University
Multi-satellite and ground-based instrument data assimilation analysis of shears in the low thermosphere

Enhanced shears in the lower thermosphere, just above the mesopause, are an important mechanism for generating instabilities, triggering turbulence and transport of energy and mass between the mesosphere and thermosphere (Mesquita et. al., 2020). These shears have been measured (Larsen 2002) and modeled (Liu 2017); however, the observations are generally localized and the free-run model results are not constrained by measurements. Recent in-situ neutral wind profile observations show shears as the triggering mechanism of a Kelvin-Helmholtz instability, which then resulted in turbulence and mass/energy transport between the mesosphere and thermosphere (Mesquita et. al., 2020) and are an integral part in the production of sporadic-E layers (Larsen et. al., 2005). The lower thermospheric shears are a manifestation of upward propagating and in-situ tides and gravity waves (Liu 2017), both of which are intrinsic to the atmosphere. While both shears and instabilities have been observed in the thermosphere there is no study characterizing the position of enhanced shears and the resultant higher likelihood of instability occurrence. Climatological models such as the Horizontal Wind Model (HWM) fail to reproduce these shears and cannot be used to assess the behavior of this important phenomenon. Therefore, the main goal of this proposed work is to find when and where shears are enhanced on a global scale. This focuses on the AIMI Science Goal 2 present in the Heliophysics Decadal Survey (National Research Council, 2013) – How does lower atmosphere variability affect geospace?

The methodology is based on the assimilation of TIMED/SABER and ICON/MIGHTI (along with additional ground-based observations) to constrain the large-scale dynamics in high-resolution runs of the Whole Atmosphere Community Climate Model (WACCM-X). The data assimilation tool to be used is the Data Assimilation Research Testbed (DART), an open-source data assimilation tool developed and maintained by Data Assimilation Research Section (DAReS) at the National Center for Atmospheric Research (NCAR). This data assimilation tool supports the use of the coarse resolution WACCM-X, which does not have fine enough resolution to produce shears comparable with observations in the low thermosphere (Liu 2017). However, the coarse-resolution WACCM-X+DART will be used to constrain large-scale flows in the high-resolution WACCM-X run. That allows us to perform observationally constrained high-resolution WACCM-X simulations. The high-resolution WACCM-X output will be compared with the wind shears from ICON. A statistical analysis of the high-resolution WACCM-X output will be done. The regions of enhanced shears will be highlighted for solstices and equinoxes. We intend to investigate and characterize this crucial physical process in the thermosphere and unveil the global regions where there is a high likelihood of vertical transport of mass and energy.

Larsen, M. F., Winds and shears in the mesosphere and lower thermosphere: Results from four decades of chemical release wind measurements, J. Geophys. Res., 107 (A8), 2002.

Larsen, M. F., Yamamoto, M., Fukao, S., Tsunoda, R. T., and Saito, A.: Observations of neutral winds, wind shears, and wave structure during a sporadic-E/QP event, Ann. Geophys., 23, 2369–2375, 2005.

Liu, H.-L. Large wind shears and their implications for diffusion in regions with enhanced static stability: The mesopause and the tropopause. Journal of Geophysical Research: Atmospheres, 122, 9579–9590, 2017.

Mesquita, R. L. A., Larsen, M. F., Azeem, I., Stevens, M. H., Williams, B. P., & Collins, R. L., et al. In situ observations of neutral shear instability in the statically stable high-latitude mesosphere and lower thermosphere during quiet geomagnetic conditions. Journal of Geophysical Research: Space Physics, 125, 2020.

National Research Council. Solar and Space Physics: A Science for a Technological Society, p168, 2013.

Mahboubeh Asgari-Targhi/Smithsonian Institution/Smithsonian Astrophysical Observatory

Unraveling the dynamics of the slow wind using magnetohydrodynamic modeling and observational constraints

We propose a combined modeling and observational study to determine how Alfven-wave turbulence heats the corona and the accelerates the slow solar wind. Theoretical models posit that Alfven waves traveling outward from the Sun are reflected by gradients in the Alfven speed.

These reflected waves interact nonlinearly with the outward-propagating waves to produce turbulence, which causes a cascade of wave energy to small length scales where the energy is dissipated.

In our previous study of polar coronal holes and the fast solar wind, we showed that large-scale Alfven-speed gradients due to the falloff of magnetic field and plasma density are too weak to drive sufficient turbulence to explain coronal heating. However, the wave reflection could be enhanced to a sufficient level by incorporating observationally constrained small-scale density fluctuations into the model.

Here, we will explore whether the conditions of the equatorial corona are capable of generating sufficient Alfven-wave turbulence to account for the acceleration of the slow solar wind. We will use a reduced magnetohydrodynamic (RMHD) model with inputs that are constrained by observations. Our model considers a flux tube that extends from the coronal base out to 20 solar radii. The initial conditions are a background atmosphere constrained by observations. The magnetic field is determined using our Coronal Modeling System (CMS), which extrapolates the observed photospheric magnetic field strength to large heights based on a potential field approximation. Alfven waves are excited at the base of the corona and evolved by solving the RMHD equations. From the solutions we calculate the heating rate and various parameters describing the turbulence that can be directly compared with in situ measurements, such as the Alfven ratio, residual energy, and cross helicity.

We will determine how the large-scale magnetic field profiles B(r) of slow wind source regions influence the development of Alfvenic turbulence. In situ observations find that the Alfvenicity of the slow wind varies by source region and that solar wind is more Alfvenic closer to the Sun. This suggests that turbulence develops closer to the Sun in some source regions than others, resulting in more rapid dissipation and loss of Alfvenicity as the solar wind flows outward. We will use our model to simulate Alfven-wave turbulence for B(r) profiles from various slow wind sources, including boundaries of equatorial coronal holes, low latitude extensions of polar coronal holes, and pseudostreamers. We will quantify how the large-scale magnetic field gradients in those sources change the rate at which turbulence develops and determine whether this can account for the observed variations in Alfvenicity.

We will also investigate the influence of small-scale density fluctuations, which we previously found were critical for promoting turbulence in fast wind sources. To measure the characteristics of density fluctuations in slow wind sources, we will analyze data from Hinode, IRIS, AIA, and PSP. We will focus on observations taken during PSP perihelia, allowing us to characterize density fluctuations in the low corona based on the remote sensing data (e.g., Hinode, IRIS, and AIA) as well as at larger distances of 10-20 solar radii using PSP. We plan to first analyze a coordinated observation from PSP encounter 8, for which we have a comprehensive set of observations focusing on several low-latitude coronal holes and later extend the analysis to other PSP perihelia.

The observed density fluctuations will then be incorporated into the RMHD model. We will examine how observed density fluctuations affect the wave heating rate in slow wind sources and influence the properties of the slow solar wind.

This work is directly relevant to NASA's Heliophysics program goal to "Explore and characterize the physical processes in the space environment from the Sun to the heliopause..."

Jan Egedal/University Of Wisconsin, Madison
Electron Energization by Magnetic Pumping Explored Through MMS Data

The transport of matter and radiation in the solar wind and terrestrial magnetosphere is a complicated problem involving competing processes of charged particles interacting with electric and magnetic fields. The existence of superthermal particles has been confirmed throughout our solar system including observations beyond the termination shock by Voyager 2. The understanding and prediction of the behavior for high energy (superthermal) particles is particularly important as these particles represent the greatest threat to human exploration of the solar system and to our deep space missions.

Motivated by MMS spacecraft observations our group has shown that magnetic trapping renders pumping effective for superthermal electrons. We propose to further investigate the relevance our new pumping model to in situ spacecraft observations at the Earth's bow shock. The model in Refs. [1,2] requires relatively strong pitch angle scattering for the mechanism to become effective. In contrast, our most recent publication on the subject considers more general configurations including interacting magnetic perturbations with various phases and amplitudes. We find that parallel mixing here causes the heating by pumping to become much more effective in environments with low levels of pitch angle mixing. Furthermore, the theory provides signatures that can be evaluated to infer directly from the space craft observations the level of pitch angle mixing applicable in a given environment [3]. Data recorded by NASA's MMS mission during hundreds of bow shock crossings is uniquely situated suited for this analysis. Not only are these an ideal place to observe magnetic pumping, but MMS's order of magnitude increase in temporal resolution in electron and ion velocity measurements makes it easier to detect the signatures of magnetic pumping. In fact, signatures of magnetic trapping are readily observed in the electron distribution functions recorded at high fidelity by MMS; we foresee that their analysis will guide and contain the development of magnetic pumping as a general heating mechanism in heliophysical and astrophysical plasma settings.

The theoretical development of the pumping model will be led by Dr. Jan Egedal and aided by a TBD graduate student at UW-Madison, as well as former graduate student Dr. Emily Lichko. The research will be guided by kinetic simulations by Ari Le, as well as spacecraft observations. Thus, we will employ fully kinetic simulations as well as advanced kinetic theory to extend the pumping model into the regime $v \gg \omega/k$, where the MMS data now suggests that pumping is likely to be effective.

Given the ubiquity of magnetic fluctuations in different astrophysical systems, the pumping mechanism has the potential to be transformative to our understanding of how the most energetic particles in the universe are generated. As such, the proposal is relevant to the actions under Goal 1 and 4 for Solar and Heliospheric Physics in the last Decadal Survey:

Goal 1: Determine the origins of the Sun’s activity and predict the variations in the space environment

Goal 4: Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe.

[1] E. Lichko, and J. Egedal, "Magnetic pumping model for energizing superthermal particles applied to observations of the Earth's bow shock," Nature Comm., 11, 2942, 2020.

[2] J. Egedal, E. Lichko, “The Fast Transit-time Limit of MagneticPumping with Trapped Electrons”, accepted, Jour. Plasma Phys., 2021.

[3] J. Egedal, J. Schroeder, E. Lichko, “Parallel velocity mixing yielding enhanced electron heating during magnetic pumping”, Jour. Plasma Phys. 87, 905870116, 2021.

Xiangrong Fu/NMC, Inc.

Density Fluctuations in Near-Sun Solar Wind Turbulence

Science Goals and Objectives

The solar wind is a turbulent plasma originating from the upper atmosphere of the sun. Due to the magnetic field penetrating the solar wind, the turbulence exhibits strong anisotropy and it has been most thoroughly studied in the framework of incompressible magnetohydrodynamics (MHD), assuming only Alfvenic fluctuations and no density variation. However, in-situ observations clearly show density variations consistent with a compressible component in the solar wind, especially close to the Sun where the turbulent Mach number is large. In fact, compressible turbulence, although poorly understood, has much richer physics including density/pressure variation, multiple wave modes, various nonlinear wave-wave interactions, and multiple energy dissipation channels. The proposed work will address origins of density fluctuation as manifested in the complex compressible turbulence in the near-Sun solar wind. Our recent studies show that a large fraction of the density fluctuation is not from compressible waves, as suggested in the traditional view. The fluctuations do not follow linear dispersion relations, but instead appear to be nonlinear structures. This result prompts us to re-evaluate the generation mechanism of density fluctuations in compressible turbulence. We will use in-situ measurements of the near-Sun solar wind by Parker Solar Probe (PSP) to characterize the properties of density fluctuations and their dependence on solar wind conditions and heliospheric distance. This study will also address the stability of nonlinear structures and dissipation of density fluctuations.

Methodology

We propose to study the properties and origins of density fluctuations in compressible solar wind turbulence using state-of-the-art 3D MHD and hybrid simulations. MHD simulations are appropriate for investigating turbulence at large fluid scales where energy is injected. Accompanying hybrid simulations will be used to study dissipation of density fluctuations near ion kinetic scales. This proposal will also use data from NASA's Parker Solar Probe (PSP) mission. Plasma data from the PSP SWEAP instrument and magnetic field and quasi-thermal-noise plasma density data from the PSP FIELDS instrument will be used to calculate power spectral densities and correlation measures. Plasma and magnetic field data from the ACE and Wind missions will be used to compare and contrast the PSP near-sun measurements with 1 AU solar wind observations. Conjunction observations between PSP and Solar Orbiter will be explored to identify signatures of compressible turbulence and its evolution in the heliosphere. Comparison between simulation and observation data is key to make sure the simulation reveals the physical process in real solar wind and the observations are properly interpreted.

Relevance of the Problem

By addressing compressible turbulence and the origins of density fluctuations, the proposed research is highly relevant to one of the objectives of the HSR program: "Explore and characterize the physical processes in the space environment from the Sun to the heliopause and throughout the universe". The proposed work, which includes both numerical simulation and data analysis of NASA missions (PSP, ACE, WIND), is aligned with the HSR program.

Dale Gary/New Jersey Institute Of Technology

Solar Flare Transport Processes Deduced from NASA Data and Microwave Imaging Spectroscopy

Objectives of the project: This proposal seeks support for a focused program of research on fundamental solar flare processes via analysis of NASA data augmented by microwave imaging spectroscopy and advanced 3D modeling and forward fitting. A specific goal of the project is to obtain quantitative information of the transport of particles within the flaring environment and what mediates that transport. This involves measuring the dynamic changes in the parameters of the flaring environment, such as magnetic field and fast electron distribution, and tracking how they evolve on time scales down to 1 s. We will use this information to infer the basic processes occurring in flares, and supply the NASA community with the data, data products, and results of analysis thereof.

Significance: This proposal addresses one of the high priority problems in solar physics: the basic mechanisms of solar flares, focusing on spatial and temporal evolution of energetic particles over a wide range of energy, from thermal to relativistic. This research is timely: the unique combination of new and ongoing space instruments (STIX, AIA, HMI, FIELDS and ISOIS) provide diagnostics on the nonthermal electrons, thermal plasma and surface magnetic fields, and in situ measurement of fields and particles, respectively, to which will be added our unique and complementary diagnostics of coronal magnetic field, particles, and thermal plasma from microwave imaging spectroscopy, for flares already observed with our Expanded Owens

Valley Solar Array (EOVSA).

Relevance to NASA: This proposal addresses a NASA strategic goal to “Understand the Sun and its interactions with the Earth and the Solar System” and a NASA-specific research objective to “Understand the fundamental physical processes of the space environment from the Sun to Earth, to other planets, and beyond to the interstellar medium.” The focused program of solar flare studies with multi-wavelength data as proposed here is explicitly and highly relevant to the first goal of the Heliophysics Decadal Survey, “Determine the origins of the Sun’s activity and predict the variations in the space environment” and to the fourth Decadal Survey goal, “Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe.”

Methodology: We employ a combination of multi-messenger space data with auxiliary coronal magnetic field and particle measurements available from microwave imaging spectroscopy at hundreds of frequencies over 1-18 GHz. The combined data are used with our GX Simulator 3D modeling tools to create temporally-evolving 3D models matching all the available observational data.

Proposed work: We will study the acceleration and transport of nonthermal electrons via comprehensive data analysis augmented by time-dependent 3D modeling of a number of solar flares jointly observed by SO, SDO, PSP, EOVSA, and other instruments. We will use an already substantial database of jointly observed flares with STIX (hard X-rays) and EOVSA (microwaves) to trace the dynamic evolution of the electron distribution both spatially and in energy to reveal the transport processes that operate in the flaring environment. We will incorporate these insights in our existing 3D modeling tools to investigate what the transport reveals about energy release and evolving magnetic connectivity in the flaring environment.

Team: To attack the project objectives we bring together a highly qualified team of experienced researchers, which collectively possess all the observational, theoretical, and modeling expertise needed to fully achieve the project goals.

Katelynn Greer/University Of Colorado, Boulder

Characterizing and Understanding the Molecular Oxygen Density Structure of the Lower Thermosphere Through Observations and Models

The lower thermosphere’s composition is dominated by N2, O, and O2. Photodissociation of O2 by ultraviolet (UV) radiation in the thermosphere produces O. Further dissociation of O produces O+ and an electron. Oxygen chemistry and UV radiation are critical for determining plasma densities in the ionosphere. However, historical observations of O2 are sparse, especially in the lower-to-middle thermosphere, leading to disparate model results compared to observations.

While the widely-used empirical MSIS models incorporate O2 from the Atmosphere Explorer missions and other sources, there are limitations with these data. For example, some data from in-situ mass spectrometers can give inaccurate O2 density measurements. Secondly, extant O2 measurements are from remote sensing solar occultations, provide only limited local time-latitude coverage. Several thermospheric general circulation and whole atmosphere models (e.g., WACCM-X and TIE-GCM) also do not accurately reproduce O2 densities. Publicly available O2 stellar occultations from Global-scale Observations of Limb and Disk (GOLD), provide a more accurate and complete dataset to evaluate the accuracy of O2 within models and its impact on thermosphere-ionosphere (TI) system. GOLD O2 observations are available for 2019-2021, between 130-200km, for all local times and seasons. Initial analysis of GOLD O2 shows extraordinary structure in local time, season, latitude, and altitude that is not captured in widely-used empirical and first-principles models. In particular, GOLD observations show a distinct diurnal structure with local time not reproduced by neither MSIS2.0 nor TIE-GCM.

In the proposed work, we seek to characterize and explain the variability of O2 in the lower thermosphere as a function of local time, season, latitude, and altitude. To provide science closure on our objective, we seek to answer the following questions:

(1) What is the observed O2 structure in the lower thermosphere as a function of local time, season, latitude, and altitude?

(2) What are the relative roles of atmospheric tides and in-situ temperature variations in producing the observed local time structure of lower thermospheric O2?

(3) To what extent does O2 variability between 100-200 km effect the variability in the thermospheric and ionospheric composition and temperature?

To answer these questions, we will employ GOLD O2 density profiles, the MSIS2.0 model, and the NCAR thermosphere general circulation models: the TIE-GCM and TIME-GCM, with the latter constrained by lower and middle atmospheric reanalysis datasets. The GOLD O2 and disk temperature data will first be examined to quantify prominent structures as a function of local time, season, latitude, and altitude. GOLD-MSIS comparisons in O2 and temperature will be performed to determine systematic biases and standard deviations between GOLD and MSIS in O2 and temperature, as well as other datasets in the MSIS database. This will assist in elucidating what mechanisms could be responsible for driving the O2 and temperature variations observed by GOLD, as well as inform our numerical experiments. Force term analysis of numerical TIME-GCM and TIE-GCM simulations will allow us to determine the relative roles of vertically-propagating tides, in-situ tides, and neutral temperature on the spatiotemporal distribution of O2 density in the lower thermosphere. Additional numerical experiments will be performed to quantify the effects of O2 density variations in the lower and middle thermosphere on pertinent TI parameters, including E-region ion and electron densities, O, temperature, as well as the overlying impacts of the upper TI.

This proposed work supports the objective in B.1, of “investigations of the physics of the terrestrial mesosphere, thermosphere, and ionosphere, neutral and ionized, and coupling of these phenomena to the lower atmosphere and magnetosphere.”

Adam Kellerman/University of California, Los Angeles
Event-driven Modeling of Earth's Radiation Belts

It has been long observed that key physical processes, such as plasma density, magnetic field, and wave power, which control the dynamics of Earth’s radiation belts vary spatially and temporally on the order hours or less. However, due to computational limitations it has been common to use only statistical estimates of these processes and a dipole approximation, for quasi-linear diffusion coefficient computations, necessary for diffusive modeling of the radiation belt system. Hence, this variability has never been truly captured in our simulations, and our understanding of the importance of each physical process has been cloaked by the introduced error and bias.

The goal of the proposed effort is to employ time and space-varying parameters to fully quantify the geomagnetic-activity-dependent importance of (a) wave type and intensity, (b) plasma density, and (c) magnetic field, in driving non-adiabatic electron acceleration and loss in Earth’s radiation belts.

Methodology

The quasi-linear diffusion coefficients are originally computed using the UCLA Full Diffusion Code, and then compiled into a parametric model that allows a fast look-up-table approach to be employed. The fast quasi-linear diffusion coefficient computations accurately reproduce results from the traditional computation methods but are over 250,000 times faster. The diffusion coefficients are then ingested into VERB4D and UCLA diffusion code simulations to specify the radiation environment. The model initial and boundary conditions utilize multi-spacecraft bias-corrected phase space density dataset, including THEMIS, Van Allen Probes, GOES, GPS, Cluster, and MMS observations. Empirical wave data are obtained from the same set of spacecraft. Event-specific wave power, as a function of L and MLT is obtained from the POES spacecraft, and recently developed machine learning models. Event-specific density is also derived from a recently developed machine learning model.

Simulations will employ an ensemble-based short-term analysis method, that relies on distributions of our initial conditions, boundary conditions, and model parameters. Using median-symmetric accuracy and signed-symmetric percentage bias, we will determine the optimal ensemble member for each time period, and the conditions and parameters, which minimize the model error and bias. We will also compute the standard deviation in our ensembles to determine the sensitivity of the simulations to the conditions and parameters under different geomagnetic conditions. The best simulation will then be used as a restart initial condition for the next time period. Verification will employ in situ flux observations from Van

Allen Probes, GOES, and GPS spacecraft across multiple energies and L-shells. A variable and sliding window of simulation start time will be used to investigate any dependence on the time scale, and to ensure that there's no bias as a result of the start time used. The results will be combined into new parametric models that will allow event-specific modeling for historic periods and in near real-time applications.

Relevance

The proposed effort will resolve the importance of magnetospheric waves and plasma conditions across multiple geomagnetic conditions, by performing extensive physics-based modeling based on the data from NASA spacecraft missions. Our proposal will address the specific objectives 1 and 3 of NASA Heliophysics Research Program. The analysis technique will allow exploration of characterization of the physical processes in the space environment. The ensemble-driven model will develop the knowledge and capability to detect and predict extreme conditions in space to protect life and society and to safeguard human and robotic explorers beyond Earth.

Kalman Knizhnik/Naval Research Lab
Flux Emergence from the Convection Zone to the Corona: Understanding the Roles of Convection and Buoyancy

It is generally agreed that magnetic flux is created deep in the solar interior by a dynamo process, whereupon it rises to the surface due to a combination of buoyant and convective forces. At the photosphere, the magnetic flux is observed as an active region, which expands into the corona where it supplies the magnetic energy for solar eruptive events. The challenges for understanding this process, especially the disparate time and spatial scales involved in thermal transport in the convection zone and corona, have heretofore prevented numerical models from fully capturing the interplay between buoyancy, convection, and flux emergence from the convection zone into the corona. Existing simulations have either been primarily focused on including convection in the upper convection zone and ignore the corona, or include the entire upper convection zone and corona but assume only buoyant processes are responsible for the emergence of flux, while ignoring key thermodynamic processes such as thermal conduction and radiation. As a result, a complete picture of flux emergence, spanning the upper convection zone-to-corona region, remains elusive. However, with the advent of faster computational capabilities and newly developed numerical schemes, we can now simulate processes which incorporate the physics of both thermal conduction and radiation as well as buoyancy in the entire upper convection zone-to-corona region. In this proposed project, we will simulate the rise and emergence of twisted flux ropes subject to both buoyant and convective forces during their rise and emergence from the convection zone into the corona. We will run the simulations with and without convection, in order to understand its role in the entire flux emergence process. We will examine the photospheric signatures produced by this emergence and compare them quantitatively with SDO/HMI observations of emerging active regions to determine what processes are important for flux emergence on the Sun.

Science Goals and Objectives:

Goal 1: Investigate the roles of buoyancy and convection in the rise of magnetic flux ropes by simulating the rise of weakly or moderately twisted magnetic flux ropes through the convection zone with and without convection.

Goal 2: Investigate the roles of buoyancy and convection in the emergence of magnetic flux ropes through the photosphere by simulating their emergence with and without convection.

Goal 3: Observationally constrain quantitative properties of certain active regions, throughout their evolution, to better understand the physical processes involved in their formation.

Relevance to Decadal Survey Goals:
By investigating the rise of magnetic flux ropes with and without convection, and then by investigating the observational signatures that these emerging flux ropes at the photosphere, this project directly attacks the Decadal Survey goal: "Determine the origins of the Sun's activity and predict the variations of the space environment."

Methodology:

Three primary types of science investigations will be carried out to perform the proposed investigation.

1. The buoyant, convection free rise and emergence of magnetic flux ropes will be carried out by Knizhnik, assisted by Leake, using the Lagrangian Remap 3D (Lare3D) MHD code.
2. The rise and emergence of magnetic flux ropes subject to convective motions will be carried out by Knizhnik, assisted by Leake, using the Lare3D MHD code that has convection incorporated into the governing equations by Daldorff and Johnston.
3. Solar Dynamics Observatory/Helioseismic and Magnetic Imager (SDO/HMI) data will be used by Norton to identify the structure and dynamics of emerging active regions, and relate these to the simulation results. If HMI spatial resolution is insufficient, the higher resolution Hinode Narrowband Filter Imager (NFI) data (prior to Feb 2016) will be utilized as needed.

Bharat Kunduri/Virginia Polytechnic Institute & State University
An examination of magnetosphere-ionosphere coupling during STEVE and SAID

Introduction:
Strong Thermal Emission Velocity Enhancement (STEVE) is a recently discovered optical feature that is reported to be observed at sub auroral latitudes in the pre-midnight sector. It is prominently observed in citizen science photographs and all sky imagers as a purple or mauve arc that is roughly east-west aligned. Previous works suggested that STEVE is associated with

Sub Auroral Ion Drift (SAID). Only a handful of studies have analyzed this newly discovered feature and even fewer studies have focused on determining the relation between STEVE and other collocated geophysical features such as plasma convection, Field-Aligned Currents (FACs), and the mid-latitude trough. Our understanding of STEVE is currently very limited and mostly based on event analysis. It has been hypothesized that STEVE:

1. Occurs during “extreme” SAID events when convection speeds exceed a few km/s, even though they are observed during a broad set of geomagnetic activity levels (specified by Dst and auroral indices).
2. Occurs predominantly during the substorm recovery phase.
3. Is associated with a sharp increase in electron temperature and a decrease in electron density.

The hypotheses summarized above, however, have the following shortcomings and limitations:

1. The hypotheses are based on event analysis and lack comprehensive validation.
2. It is not validated if all “extreme” SAID events drive STEVE.
3. The role of crucial geomagnetic factors such as FACs and the mid-latitude trough (which play an important role in driving SAPS/SAIDs) in driving these “extreme” SAIDs and STEVE has not yet been analyzed.

Datasets and models:

1. Van Allen Probes (Electric Fields and Waves instrument)
2. Multiscale Atmosphere-Geospace Environment (MAGE) model
3. Super Dual Auroral Radar Network (SuperDARN)
4. Active Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE)
5. Global Positioning System (GPS) Total Electron Content (TEC)
6. THEMIS ASI and REGO ASI
7. Publicly available citizen scientists observations (https://osf.io/cgqyf/)

Science goals and Methodology:

We propose to validate and test these hypotheses and develop a characterization of large-scale magnetosphere-ionosphere coupling during STEVE and SAID, using the recently developed databases of STEVE. Specifically, we will use the dataset of SAPS and SAID events observed by SuperDARN and Van Allen Probes to determine the differences in speeds and location in SAID events that produce STEVE as compared to the entire database. Furthermore, we will statistically validate if the mid-latitude trough observed in GPS TEC measurements is indeed significantly deeper during STEVE and by what factor. The role of Region-2 FACs and the substorm current wedge, determined using the AMPERE dataset in driving the SAID flows that produce STEVE will also be examined. Finally, we will use the MAGE model to examine the magnetosphere-ionosphere conditions that favor the formation of the extreme “SAID” events that are associated with STEVE emissions. If STEVE are indeed produced by a certain category of “extreme” SAID events, then specific features distinguishing such events from the other “non-STEVE” SAID events should become evident in the data analysis and modeling work we propose.

Relevance:
The proposed work is directly relevant to the overarching goal of the Heliophysics program which is to “to understand the Sun and its interactions with the Earth and the Solar System, including space weather” as it will improve our “understanding” of “sub-auroral space weather”. The proposal is also directly relevant to the first objective which states “Explore and characterize the physical processes in the space environment from the Sun to the heliopause and throughout the universe” since it will “explore and characterize” the large-scale magnetosphere-ionosphere “processes” in the near-Earth “space environment”.

Ilya Kuzichev/New Jersey Institute Of Technology
Whistler wave generation around plasma injections

Science goals
Whistler waves play fundamental role in controlling the Earth’s inner magnetosphere dynamics. They are typically observed in a form of quasi-monochromatic emissions in lower and upper frequency bands separated by a gap around a half of the electron cyclotron frequency. The energy source for generating whistler waves is provided by injections of temperature anisotropic electrons penetrating to the inner magnetosphere from the magnetotail. There is currently no accepted view on the factors controlling generation, properties and macroscopic effects of whistler waves in the inner magnetosphere. The Van Allen Probes and THEMIS observations have provided reliable measurements of the properties of electrons in injections and shown that injected electrons typically consist of several electron populations with distinct temperature anisotropies. The effect of these multiple populations on the generation and properties (frequency, amplitude, spectral width, and growth rate) of whistler waves needs to be analyzed through simulations and comparison with in-situ observations. Such analysis should also provide a better understanding of how a gap at a half of the electron cyclotron frequency is formed, whether it is due to multiple electron populations, or non-linear effects are required. In the course of generation, whistler waves modify the distribution function of injected electrons (in a different way for the various electron populations) and, therefore, should affect the macroscopic parameters of electrons in injections. There has been no detailed analysis of this effect, although it affects both generation of whistler waves in the course of inward propagation of injections and properties of electrons finally injected to the inner magnetosphere. The synthesis of comprehensive Particle-in Cell (PIC) simulations and a wealthy of spacecraft observations of injections in the Earth’s inner magnetosphere make it possible to address generation and effects of whistler waves in injections, which is the scientific goal of this proposal. This scientific goal requires to address the following questions:
1. What are electron distribution functions responsible for whistler wave generation around plasma injections?
2. What are typical characteristics of whistler waves generated around plasma injections?
3. What is the contribution of whistler waves to electron distribution evolution at injections fronts?

Methodology and data analysis

The theoretical methodology of the project is based on the 2D PIC code TRISTAN-MP that will be used for simulation of whistler wave generation and nonlinear evolution. The theoretical methodology will also include analysis of linear dispersion relation and instability criteria that is based on the linear plasma dispersion solver. A statistical analysis of properties of electrons in injections will be carried out using 6 years of Van Allen Probes (HOPE and MAGEIS detectors) and over 9 years of THEMIS (ESA and SST instruments) data. The properties of whistler waves will be determined using measurements of EMFISIS and EFW instruments aboard the Van Allen Probes and FBK and FFT data provided by THEMIS spacecraft.

Relevance of the problem to one or more of the Decadal Survey Goals

The goal of this proposal is to provide a complete understanding of the factors controlling the generation of whistler waves in injections. This goal is related to basic goals of Van Allen Probes mission, because whistler waves is one of the leading factors controlling the dynamics of the outer radiation belt. This work contributes to two of the four Scientific Objectives of the Heliophysics Decadal Survey, namely "Determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs" and "Discover and characterize fundamental processes that occur both within the heliosphere and throughout the Universe".

KD Leka/NorthWest Research Associates, Inc

Up, Up & Away! Relating Early CME Acceleration to Coronal Magnetic Topological Features.

Up, Up & Away! Relating Early CME Acceleration to Coronal Magnetic Topological Features.

Science Objectives and Goals:

Something, or somethings, unknown as of yet, govern when a solar energetic event will be allowed to accelerate plasma into the heliosphere as a coronal mass ejection (CME), and when that acceleration will not be allowed to do so. Many studies and models have examined different options including whether there is sufficient (too much) flux above a flux rope, sufficient (too much) magnetic flux or mass or twist involved, the proximity of open field and (or?) the number of magnetic null points. The properties of CMEs, as deduced from coronagraph images, are correlated with the characteristics of coronal dimmings that usually accompany them, but the acceleration profile of CMEs is largely unknown. We propose three science goals: (1) thoroughly describe the chromosphere kinematics of energetic events, differentiating between CME-productive, CME-failed, and the non-event chromosphere, (2) test whether plasma acceleration is dependent on the presence or absence of specific magnetic topological features, and (3) solidify (or refute) the links between plasma acceleration, coronal signatures of a CME, the topological context, and the properties of the final heliospheric-propagating CME.

Methodology:

The targets for this study will be CME-productive active regions and controls of CME-less events and event-quiet epochs. To map the low-atmosphere plasma acceleration we use a large database of Mees CCD Imaging Spectrograph data (www.nwra.com/MCCD) that recorded rapid-cadence AR-sized imaging spectroscopy in Halpha from 1989 -- 2005. With a 1.8nm-wide spectral sampling range and sit & stare default observing mode, MCIS data provide quantitative measures of the earliest event-related plasma dynamics, and direct evidence of filaments (and their formation) from which the CME derives its "M". MCIS data sample a large number of regions and events; many years overlap with the Solar and Heliospheric Observatory (SoHO). Michelson Doppler Imager (MDI) data will be the primary source of photospheric field maps from which Magnetic Charge Topology and Potential-Field Source-Surface models will be used to characterize the topological environment into which the target events erupt (or not). EUV Imaging Telescope (EIT) data will provide quantitative low-coronal characteristics of the events, and databases of CME properties derived from the Large Angle and Spectrometric Coronagraph Experiment (LASCO) will provide the terminal properties of the CME (or not). Finally, with control targets consisting of CME-less flares and event-less periods from the same target active regions, the NWRA Classification Infrastructure (NCI), a discriminant-analysis based statistical facility, will be used to address the question of what features best decide the fate of a CME; correlation analysis will address the relationship between CME acceleration properties, coronal dimming properties, topological context, and the plasma eruptivity.

Relevance:

We propose to address all three NASA Heliophysics Research Program Objectives, "Explore and characterize the physical processes in the space environment", "Advance our understanding of the Sun's activity", and "Develop the knowledge and capability to detect and predict extreme conditions". The proposed work focuses on fundamental questions of physical processes on the Sun (what allows a CME to accelerate?), using a unique ground-based dataset coupled with NASA mission archive data; the outcome of the research could enable the capability to predict when the magnetic and plasma conditions are right (or not) for a CME to occur.

Terry Liu/University of California, Los Angeles
Predictive Model of Hot Flow Anomalies and Foreshock Bubbles

Predictive Model of Hot Flow Anomalies and Foreshock Bubbles

1. Introduction

Foreshock transients are frequently observed in the ion foreshock. The most significant ones are hot flow anomalies (HFAs) and foreshock bubbles (FBs) due to their large spatial scales and substantial plasma deflection and heating. They have been shown to disturb the local bow shock through significant dynamic pressure perturbations, which further disturb the magnetosheath, magnetopause, and consequently the magnetosphere-ionosphere system. Recent studies also found their significant roles in particle acceleration, potentially contributing to shock acceleration. Despite their important roles, so far there exists no predictive model for the occurrence and effects of HFAs and FBs. Establishing quantified models of HFAs and FBs is crucial for their inclusion in the space weather models and shock models.

Our recent PIC simulations of foreshock kinetic physics and MMS observations identified a physical mechanism for the formation of HFAs and FBs as follows. Due to the presence of a discontinuity near the bow shock, demagnetized foreshock ions result in a Hall current and the associated magnetic field profile. If the field variation can trap more foreshock ions and further demagnetize them, Hall current will be enhanced, which causes further magnetic field variations. The resulting positive feedback loop enables the growth of HFAs and FBs. The magnetic field variation induces an electric field that drives an outward motion of cold plasma together with field lines, i.e., expansions of HFAs and FBs. Our formation model provides a possibility to quantify and thus predict the formation and expansion of HFAs and FBs.

2. Science Goals and Objectives

The goals of our proposed project are to:

(a) Quantify the formation criteria of HFAs and FBs. To predict the formation of HFAs and FBs, we will examine their formation conditions quantitively, e.g., examine the magnetic field configuration and foreshock ion distributions needed to initiate the positive feedback loop and thus the growth of HFAs and FBs. We will also determine the growth rate of HFAs and FBs as a function of ambient plasma and field parameters, which should be fast enough before other instabilities overwhelm the background field variation and before the driver discontinuity leaves the foreshock.

(b) Predict the expansion speed of HFAs and FBs as a function of solar wind and foreshock parameters. The expansion speed determines how large HFAs and FBs can become and thus how significant their geoeffectiveness can be. The expansion speed also determines the presence of shocks associated with HFAs and FBs, which is critical to their particle acceleration. Prediction of the expansion speed can thus help predict their contributions to the space weather effects and shock acceleration.

3. Methodology

We will analyze in-situ observations in the Earth's foreshock using THEMIS and MMS missions with more than 300 events in our database. We will also use comprehensive PIC and hybrid simulations with well-tested codes to study the formation of HFAs and FBs under various conditions. We will derive a theoretical model and validate it based on our observation and simulation data. Our team has extensive experience in all aspects of this project, including the observations, simulations, and theory.

4. Relevance to Heliophysics Overarching Goal

Our proposal is directly relevant to all three objectives in HELIOPHYSICS RESEARCH PROGRAM B.1. We explore the physical formation process of foreshock transients at planetary shocks (objective #1). Foreshock transients are part of the solar wind-planetary magnetosphere coupling, which highly depends on the variable solar wind conditions (objective #2). Our formation model can help detect and predict the space weather effects and energetic particles generated by foreshock transients (objective #3).

Xu Liu, /University Of Texas, Dallas

Investigating the role of lightning-generated whistlers in radiation belts

Resonant interactions of trapped energetic electrons in the inner radiation belt and slot region with lightning-generated whistlers (LGW) cause pitch angle diffusion, leading to scattering of those electrons into the atmosphere. There exist two modes of propagation of LGW waves in the magnetosphere, ducted or nonducted. The former ducted mode requires the presence of density irregularities, which makes the wave energy nearly along the magnetic field line (and small wave normal angles) and may be more effective in pitch angle scattering. The nonducted mode does not require density irregularities and leads to smoothly varying and large wave normal angles. Different propagation modes result in distinct spatial distributions of wave power and wave normal angle characteristics, and therefore lead to distinct electron scattering efficiency. Understanding propagation characteristics of LGWs and developing the accurate LGW wave model are critical in evaluating the effect of LGWs to energetic electrons in the inner belt and thus predicting the radiation levels encountered by satellites in low Earth orbits. Despite much progress on improving LGW wave distribution near the equatorial magnetosphere (thanks to Van Allen Probes mission), the relative occurrences of ducted and nonducted propagation are not yet established. The information on LGW propagation modes is critical for evaluating the resultant electron scattering rate for radiation belt electrons. Various assumptions on LGW wave propagation, which are not yet verified, were made to estimate the efficiency of LGW wave scattering. In this proposed study, we will use ray tracing simulation and data analysis on the combined DEMETER, Exploration of energization and Radiation in Geospace (ERG) satellite, and Van Allen Probes wave datasets, to understand LGW wave propagation and quantify resultant electron scattering efficiency. Specifically, we propose to address the following science questions:

1. What are relative contributions of ducted and nonducted propagation for lightning generated whistlers in the inner magnetosphere?
2. How does lightning-generated whistler wave intensity evolve in the magnetosphere?
3. How do lightning generated whistlers affect the dynamics of radiation belts electrons?

For SQ1, we will use EMFISIS waveform data and ray tracing results to separate LGW signals of ducted and nonducted propagation modes, and quantify their relative contribution to LGW wave occurrence and wave power. For SQ2, we will analyze the combined LGW spectral data from VAP and ERG to obtain global distribution of LGW wave spectral power density. Furthermore, we will run ray-and-power tracing simulation with constraint from DEMETER observation to see how well we can reproduce the observed LGW distribution in the magnetosphere. For SQ3, we will develop the global model of LGW wave power and wave normal angle distribution, and use the model results to calculate electron scattering rate and precipitation loss scale due to LGW waves.

Our proposal fits well in the NASA Heliophysics Supporting Research program as it uses theory, simulations/modeling and data analysis of NASA-spacecraft to directly “investigations of significant magnitude that employ a combination of scientific techniques”. Success of the project will provide our deep understanding of the LGW wave propagation in the magnetosphere and the dynamics of the Earth’s radiation belts. Our proposal is in direct relevance to the overall objective of Van Allen Probes mission, to major science goal #2 of Heliophysics Decadal Survey, to “Determine the dynamics and coupling of Earth’s magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs.” , Objective H2 of the 2009-2030 Heliophysics roadmap: “Understand changes in the Earth’s magnetosphere, ionosphere, and upper atmosphere to enable specification, prediction, and mitigation of their effects.”

Andrey Stejko/New Jersey Institute Of Technology
Analyzing the Helioseismic Detection of Deep and Near-surface Convection

We propose an investigation that aims at addressing the current controversy spurred by the detection of anomalously weak solar convection by the Helioseismic and Magnetic Imager (HMI) aboard the Solar Dynamics Observatory (SDO). The objective of this proposal is to present the use of numerical modeling in conjunction with helioseismic analyses of data from SDO/HMI for a systematic investigation of the helioseismic techniques that have resulted in vastly different inferences of the amplitudes of solar convective scales. The primary science question addressed by this proposal is: how accurate are the helioseismic measurements of sub-surface convection, and what constraints can be placed on the observed spatial spectrum? This question is compelling because narrowing the range of inferred near-surface convective power is critical to addressing the goal of “understanding internal solar activity” as outlined in the 2018 NASA Strategic Plan. This investigation will help to develop a standard for testing helioseismic techniques, creating a robust reference for observed helioseismic signals in global mass flow regimes, and provide a new convective spectrum that will represent the best estimate for a constrained range of inferences possible with current helioseismic methods of analysis.

A brief statement of the methodology to be used, including what data, models, and analysis will be used for completing the investigation:

A newly developed compressible 3D acoustic simulation code (GALE—Global Acoustic Linearized Euler) will be employed in the forward-modeling of helioseismic techniques. This algorithm offers an efficient and flexible platform for computing the contributions of 3D background flow structures to acoustic perturbations within the simulated solar interior. The GALE code will be actuated with convective structures in different rotational regimes generated in global, non-linear, hydrodynamic simulations performed with the EULAG (EULerian/semi-LAGrangian) fluid solver. These profiles will be used for a comprehensive comparison with models of convection inferred from the helioseismic analysis of SDO/HMI data.

A systematic investigation of the time-distance deep-focusing approach, as well as two ring-diagram analysis methods, will be performed on synthetic dopplergram data produced by the GALE code and observed by SDO/HMI. These techniques will be used to recreate the convection spectrum inferred from observations and compared to helioseismic signals generated in acoustic simulations. Baselines for the maximal and minimal variances between the techniques will be explored for these subsurface convective structures, along with varying models of correlated and uncorrelated noise added to the data and generated by stochastic excitations of perturbations. This investigation will make use of NASA HECC systems to run simulations and perform helioseismic analysis.

A brief statement of the relevance of the problem to the Heliophysics overarching goal or specific objectives as described in B.1:

The detection of weak solar convection at large scales is incompatible with our current theoretical understanding as well as the results of global convection simulations. Resolving this convection controversy aims at the core of the Heliophysics Research Program’s goal of advancing our understanding of solar activity; the global interconnected processes that generate the solar dynamo and impact space weather are governed by convective solar turbulence, which plays an integral role in distributing angular momentum and maintaining differential rotation. The varying interpretations of the organization and amplitude of convective scales has serious implications for these global flows, and may necessitate a fundamental shift in how we approach the modeling of internal solar dynamics. Clearing this uncertainty represents a necessary step in advancing our understanding of solar structure.

Jason TenBarge/Princeton University
The Influence of Realistic Velocity Distribution Functions on the Dynamics and Instabilities Within Collisionless Shocks

Shocks are a key mechanism responsible for transforming super-sonic flow energy into particle energization. However, most space and astrophysical plasmas are sufficiently weakly collisional that the shocks are collisionless. In a collisionless system, it has been a grand challenge problem for more than six decades to understand how shocks process flow energy into thermal energy, thereby making the system irreversible. The instabilities generated near and through the shock drive small-scale fluctuations are responsible for scattering particles and providing an effective collisionality. Thus, the instabilities also regulate the macroscopic structure of collisionless shocks. However, since the systems are weakly collisional, the particle velocity distribution functions (VDFs) both in the vicinity of and through the shock are typically far from the canonical Maxwellian form invoked by assuming statistical equilibrium. These non-Maxwellian

VDFs can drastically alter the growth rate and types of instabilities present, yet simulations of shocks and related instabilities are initialized with isotropic Maxwellian VDFs. Therefore, we propose to study the role instabilities play in regulating the macroscopic structure of collisionless shocks and the resulting energy partitioning using continuum Vlasov-Maxwell, particle-in-cell (PIC), and hybrid PIC simulations of instabilities guided by in situ observations of shocks. Specifically, we will address the following questions:

1. How do realistic VDFs alter the macro-scale structure, heating, and energy partition of collisionless shocks?
2. What instabilities and waves are present, and how are those waves and instabilities modified by VDFs self-consistently generated at shocks?
3. How is the resulting particle energization altered by the presence of non-Maxwellian VDFs?

The methodology to answer these questions involves a coordinated investigation combining in situ spacecraft data from MMS and Wind to determine the average VDF in the vicinity of collisionless shocks with PIC (Tristan) and hybrid PIC (dHybridR) simulations of shocks employing these VDFs as initial upstream conditions. The resulting PIC and hybrid PIC simulation data in the vicinity of the shock will be used to initialize focused instability studies using continuum Vlasov-Maxwell (Gkeyll) simulations. By applying kinetic plasma theory to analyze particle energization in the spacecraft data, PIC simulations, and the continuum Vlasov-Maxwell instability studies, we will establish a comparative framework to determine the structure and energy partition of collisionless shocks using realistic particle VDFs.

Collisionless shocks are ubiquitous in space and astrophysical plasmas, and they play a fundamental role in transporting energy in systems as diverse as Earth's bow shock, the solar corona and wind, supernovae, and astrophysical jets. From observational data, we know that the particle VDFs in these systems deviate significantly from Maxwellian; however, the role these non-Maxwellian features play in governing the macro-scale structure and energy partitioning of the shocks is not understood. Therefore, by advancing our understanding of the effect of non-Maxwellian VDFs on waves and instabilities in collisionless shocks, the proposal addresses the following overarching science goal identified in the Heliophysics Decadal Survey: i) Explore and characterize the physical processes in the space environment from the Sun to the heliopause and throughout the universe.

Sanjiv Tiwari/Bay Area Environmental Research Institute, Inc.
Investigation of Heating of Coronal Plumes and Loops by Magnetic Flux Convergence and Cancellation

Science Goals and Objectives: The objective of this proposal is to investigate the role of magnetic flux convergence and cancellation in heating coronal plumes and loops. A few recent studies show that magnetic flux convergence/divergence in the photosphere directly correlates with heating/cooling of coronal plumes (Wang et al. 2016; Avallone et al. 2018). Coronal plumes are bright fan-shaped magnetic structures (long loops with only one end being visible as the plume). In a preliminary work, we find the same mechanism (heating/cooling by flux convergence/divergence) to be true for several entire coronal loops. The observed magnetic flux patches at the base of plumes and loops are predominantly unipolar, thus, may support both, wave heating (by strong field oscillation/turbulence when convergence happens), and nanoflare heating (by increased density of braided loops during the flux convergence). However, observations of small loop-like structures in otherwise unipolar magnetic flux patches suggests that mixed-polarity field is present (Wang et al. 2019). Moreover, several recent studies have found indications that bursts of coronal heating in loops can result from low-lying fine-scale sheared-magnetic-field reconnection accompanying flux cancellation near the loop feet (Tiwari et al 2014, 2019; Chitta et al 2017; Priest et al 2018).

We will use a large number of on-disk coronal plumes and non-flaring loops to answer the following questions: 1) Do all plumes and loops (or a significant number of them) get heated by magnetic flux convergence at their feet? 2) Do these plumes/loops have visible mixed-polarity field in their feet, so that flux convergence and cancellation (and/or emergence) could be involved in driving the heating? Or, is the base flux unipolar, with insignificant amount of visible minority-polarity field? 3) How do the magnetic flux convergence and cancellation in the feet of bright plumes/loops compare with that in other sites where similar flux convergence and cancellation take place but no bright plume or loop forms?

Addressing the above questions will provide new insights and constraints for coronal heating models and simulations. The overarching question is whether the heating mechanism is unipolar or not.

Mission data to be used: SDO--HMI magnetograms and AIA coronal EUV images. IRIS spectra and slit-jaw images (SJIs) of transition region (TR). Hinode SOT/SP magnetograms, and SOT/FG filtergrams.

Simulations: For better interpretations of our observations, we will use Bifrost MHD simulations of a bipolar network region, and of a coronal hole.

Methodology: We will use AIA 171 Å movies (as well as IRIS SJIs for TR) to follow evolution of coronal plumes and loops, and HMI LOS magnetograms to follow the evolution (emergence, convergence, cancellation, divergence) of magnetic flux at their base and elsewhere. We will measure rate of flux cancellation (and emergence when applicable), and quantify the flow field of the flux convergence and divergence. Hinode SOT/SP magnetograms, and SOT/FG filtergrams (when available, for a few loop feet and plume-bases), respectively, will be used for better sensitivity, and for better estimates of the flow field in the plume/loop feet. IRIS spectra will be analyzed to look for fine-scale activity differences between plume and non-plume regions having similar flux convergence and field strength on their feet. Critical magnetic field, if it exists for making plumes/loops bright, will be constrained. Publicly available MHD simulations

(Bifrost) of a network region, and a coronal hole will be analyzed to interpret our observational findings.

Relevance: Determining whether the magnetic flux convergence and cancellation on the photosphere drives heating in coronal plumes and loops falls under Science Goal 1 of the Heliophysics Decadal Survey. Moreover, flux emergence, convergence and cancellation are fundamental processes and may be included in Science Goal 4.

Arcadi Usmanov/University Of Delaware
Heating, Acceleration, and Diffusion in the Outer Heliosphere: Self-Consistent Solar Wind Modeling with Turbulence Transport, Eddy Viscosity, and Pickup Protons

This proposal lies within the Research Regime of “Heliospere”, the Science Topic is "Outer Heliosphere - Interstellar Boundary".

Science Goals and Objectives: We propose a three-year project to employ advanced global multifluid MHD simulations to study fundamental outer heliosphere problems including how the solar wind is heated, accelerated and how it evolves as it approaches and transits the outer boundaries of the heliosphere. As a priority we will examine problems relating to the Interstellar Mapping and Acceleration Probe (IMAP) mission including both global context and prediction.

Specific problems and tasks that will be addressed include:
-Development of physics-based models that account for effects of eddy viscosity and turbulent resistivity, including back reaction on flows and the resolved magnetic field, in the outer heliosphere (beyond 40 AU).
-Effects of compressible turbulence in the outer heliosphere and heliosheath.
-Structure of the heliosheath, including effects of eddy viscosity and turbulent resistivity.
-Effects of pickup protons and interstellar hydrogen on energetic particle diffusion in the outer heliosphere. Calculation of diffusion coefficients for energetic particles.
-Effect of pickup protons on the angular momentum flux carried out by the solar wind.

Exploiting these expanded capabilities will enable us to achieve our overarching goal, which is to understand how turbulence changes the properties of the solar wind plasma. We will include turbulence effects on heating and large-scale structure, and will also provide the improved parametrization that is required for energetic particle transport models. In the proposed numerical code, expanded turbulence transport and turbulent heating models will be included. All refinements to the global model will be tested against available inner and outer heliospheric observations. The global framework is driven either by (observed) representative solar magnetograms or by a tilted-dipole approximation to specify boundary conditions at the coronal base. We will apply the model to study the global properties of the solar wind plasma emphasizing its three-dimensional properties, including embedded turbulence and effects of solar activity. We will verify the simulation results for flow speed, temperature, density, etc., against spacecraft data from Parker Solar Probe, Solar Orbiter, ACE, Wind, Ulysses, and Voyager. We expect to be able to provide predictions and context simulations for IMAP to aid in the interpretation of observations, connecting single point in-situ observations to regional and global interplanetary dynamics.

Methodology: The model, which is under continual testing and refinement, allows for the self-consistent study of both large-scale structure and turbulence in the three-dimensional region from the coronal base to the distant solar wind and beyond the termination shock. The simulation code will include turbulence transport, eddy viscosity, and turbulent resistivity as well as the effects of pickup protons and will include separate energy equations for solar wind protons, pickup protons, and electrons. No artificial heat function is required. This Reynolds averaged model separates resolved and unresolved (fluctuating) fields, leading to new coupling terms such as Reynolds stresses. These couplings are modeled using eddy viscosity and resistivity terms. Analogous models for heat conduction and heat deposition due to turbulence are also employed, allowing the modeled turbulence cascade to convert fluctuation energy into heat.

Relevance to the NASA & Decadal Survey Goals: Explore and characterize the physical processes in the space environment from the Sun to the heliopause and throughout the universe; Determine the origins of the Sun's activity and predict variations in the space environment, and Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe.

Dmitri Vainchtein/Drexel University

Radiation belt losses through electron deceleration due to the nonlinear interaction with whistler-mode waves

Losses of energetic electrons in the inner magnetosphere are controlled, in part, by such non-adiabatic processes as magnetopause shadowing and curvature scattering, and electron pitch-angle diffusion into the loss-cone. The latter process is included in many global radiation belt codes by quasi-linear diffusive equations with empirical models of main wave modes responsible for scattering: whistler chorus and hiss waves, and electromagnetic ion cyclotron waves. Although the applicability of the quasi-linear theory is justified for low amplitude waves, this theory fails to explain nonlinear electron resonances with intense waves, quite often observed in the radiation belts during geomagnetically active conditions (substorm injections, CME/CIR induced storms, etc.). Of all the nonlinear resonant phenomena, the fast (drift-like) electron deceleration due to the so-called phase bunching by whistler-mode waves is one of the most feasible mechanism of “losses” for radiation belt electrons. Such a deceleration does not result in the net loss of energetic electrons into the atmosphere or magnetosheath but can rapidly reduce high-energy electron fluxes. Quantification of the phase bunching deceleration is complicated by the absence of a universal theoretical model, which would include both realistic wave characteristics (obliqueness, amplitude modulation, frequency drifts) and the interplay between the deceleration and phase trapping acceleration. Moreover, most of existing phase bunching estimates are obtained for quite coherent (chorus mode) waves, but similar effect is expected for any sufficiently intense waves, e.g., non-coherent hiss mode.

This proposal aims to develop and validate a universal theoretical model that (1) will quantify the phase bunching for relativistic electrons and a wide range of whistler-mode wave characteristics; (2) can be incorporated into existing global radiation belts models and state of art (or future) computational models that perform test particle simulations in global MHD fields. To reach these overarching goals, our proposal will achieve the following three specific objectives:
(O1) What are preferred conditions for whistler mode waves to drive electron deceleration via the phase bunching?
(O2) How the phase bunching can be described and quantified for realistic whistler-mode wave characteristics?
(O3) How do phase bunching and phase trapping affect electron life-time in radiation belts?

The proposal methodology includes:
(A) Analytical theory of the nonlinear resonant wave-particle interaction: we will combine existing Hamiltonian theory of resonances with an advanced perturbation theory to derive a universal model of deceleration rate (including a competition with phase trapping) due to the phase bunching for intense whistler-mode wave packets;
(B) Numerical simulations of electron and whistler-mode wave dynamics in radiation belts: we will use a combination of wave propagation and test particle simulations to verify and improve theoretical models;
(C) Analysis of spacecraft wave-field measurements: we will use statistics of Van Allen Probe, THEMIS, and ERG wave observations to obtain realistic whistler-mode wave characteristics and construct a parametrical model of the deceleration rate due to the phase bunching.

This proposal contributes to the Heliophysics overarching goal: “Explore and characterize the physical processes in the space environment from the Sun to the heliopause and throughout the universe”.

Leslie Woodger/Dartmouth College
Investigating the Impact of Current Sheet Scattering on Radiation Belt Relativistic Electron Loss

Earth’s radiation belts dynamic particle fluxes vary from a continuous competition between acceleration and loss. Particles are rapidly removed from the system by two main processes, wave-particle interaction and magnetopause shadowing. Specifically, relativistic electron precipitation (REP) driven by various wave modes have been extensively studied using observational data and theoretical models. Several studies show pitch-angle scattering by electromagnetic ion cyclotron (EMIC) waves as a significant loss mechanism of radiation belt relativistic electrons. Quantitative studies of REP show loss rates able to deplete drift shells of MeV electrons in the matter of hours and further deplete the entire outer radiation belt in a few days.

Another loss mechanism capable of driving REP that has not been as extensively studied is current sheet scattering. This process occurs when the radius of curvature of the magnetic field becomes comparable to the gyro-radius of the particles, leading to nonadiabatic motion. Previous theoretical and observational studies on this type of loss suggest this mechanism can be a more effective loss mechanism for relativistic electrons than loss due to wave-particle interaction. Although progress has been made through a limited number of studies, we have yet to build a more comprehensive picture of the impact of this type of loss mechanism.

We propose an investigation to characterize the impact of current sheet scattering as a loss mechanism producing REP. The volume of precipitation data collected over the past 5-10 years is significant with measurements from LEO satellites and high-altitude balloon missions such as Balloon Array for Radiation belt Relativistic Electron Losses (BARREL). NASA missions such as Van Allen Probes and THEMIS provide in-situ magnetic field and particle measurements from the inner magnetosphere. This study will compare observations of REP to theoretical estimates of loss driven by current sheet scattering in a similar way as the wave-particle investigations have been performed utilizing the Fokker-Planck equation and pitch-angle diffusion coefficients. Specifically, this study will use both conjunction events and distributed observations in comparison with theoretical estimates of loss to address the following science objectives: 1. Develop a better understanding of current sheet scattering based on multi-point conjunctive observations and modeling during varying time periods of geomagnetic activity; 2. Estimate the spatial and temporal scales of current sheet scattering; 3. Compare average precipitating electron fluxes to EMIC wave driven precipitation in order to quantify the impact of precipitation losses on the radiation belts.

The relevance of this study is highly aligned with NASA's Heliophysics' goal "to understand the Sun and its interactions with the Earth and the Solar System." Within the scope of these goals, this study addresses the objective to "advance our understanding of the Sun's…connections between solar variability and Earth…" REP is responsible for changes to our atmosphere including the production of nitric oxides and hydrogen oxides. Furthermore, these high energy electrons can cause satellite failures and thus have even been called "killer" electrons. It is important to develop an understanding of the mechanisms that drive the variability of these particles in the near-earth magnetosphere as outlined by NASA's third objective. This study will further our understanding of the impact of current sheet scattering as a loss mechanism contributing to our understanding of radiation belt dynamics and its impact on our atmosphere.

Xu Zhang/University of California, Los Angeles
Electron cyclotron harmonic waves in Earth's plasma sheet: wave generation and contribution to electron precipitation

Science Goal and Objectives

Plasma sheet (sub-keV) electron precipitation is the main source of diffuse aurora and an important element in magnetosphere-ionosphere coupling. The precipitated electrons are scattered into the loss cone mostly by whistler-mode waves (around fast plasma flows) and by electron cyclotron harmonic (ECH) waves. Previous theoretical estimates and statistical analyses have demonstrated that ECH waves are more effective than whistler-mode waves in scattering the main (sub-keV) electron population from the plasma sheet. ECH waves are thus likely responsible for a significant fraction of electron precipitation from the plasma sheet (beyond 8-12 Earth radii in the night magnetotail). All existing models of ECH wave generation and subsequent electron scattering assume the loss-cone anisotropy as the free energy source for wave generation and the associated electron scattering rates. Recent spacecraft observations in the plasma sheet, however, have demonstrated that sub-thermal electron beams, typical of ionospheric electron outflows and subsequent field-aligned acceleration, can contribute significantly to ECH wave growth with different dispersion and electron scattering characteristics. In contrast to waves generated by loss-cone anisotropy, those generated by electron beams have a much smaller wave normal angle and much larger field-aligned electric field. This newly discovered ECH mode may effectively scatter electrons not resonant with the classical (transversely propagating) ECH mode. This project aims to improve existing models of ECH wave dispersion and contribution to plasma sheet electron scattering, by comprehensively incorporating this new ECH mode into our phenomenological paradigm of plasma sheet electron precipitation and the formation of the high-latitude diffuse aurora. Specifically, the following Science Questions will be addressed:

1. What are the statistical properties and occurrence rate of different types of ECH modes in Earth's plasma sheet?
2. What are the dispersion relations of ECH waves generated by loss-cone anisotropy and by electron beams?
3. What is the relative contribution of different ECH wave modes to plasma sheet electron precipitation?

To address these questions, we will:

Methodology

i. Construct a comprehensive dataset of ECH waves observed by THEMIS and MMS spacecraft in the plasma sheet. As the propagation direction is critical in determining the wave particle resonant interaction, we will use the interferometry technique to estimate the propagation direction directly from waveforms.

ii. Conduct a comprehensive parametric analysis of the linear instability informed by realistic electron distributions measured during ECH wave intervals. Immeasurable aspects of the distribution functions (such as low-energy electron density and loss-cone width or fill ratio) will be inferred from the measured wave properties. Such analysis will provide a new model of ECH wave dispersion in the presence of multicomponent electron populations.

iii. Evaluate pitch-angle diffusion rates for different ECH modes in the plasma sheet. In the frame of UCLA Full Diffusion Code, quasi-linear diffusion rates will be calculated based on wave dispersion derived from the linear instability analysis.

Relevance

Wave-particle resonant interactions play a crucial role in electron precipitation from the plasma sheet to the ionosphere. This is especially true for the main plasma sheet population at sub-keV energies, which are only weakly scattered by the magnetic field line curvature. This project focuses on comprehensively evaluating diffusion rates of different ECH wave modes, which are also observed in planetary magnetospheres and laboratory plasmas. Therefore, our proposal is relevant to NASA Heliophysics' overarching goal and the specific objective to: “Explore and characterize the physical processes in the space environment from the Sun to the heliopause and throughout the universe”.

Lulu Zhao/University Of Michigan, Ann Arbor

Understanding Energetic Particle Acceleration and Variability in the Vicinity of Interplanetary Shocks

Energetic storm particle (ESP) events are the enhancement of energetic particle fluxes associated with passage of interplanetary (IP) shocks. These traveling IP shocks are believed to be the main accelerators for the energetic particles. However, the energy spectra integrated in the vicinity of shock often show strong variabilities and have large deviations from the prediction of standard diffusive shock acceleration. Our proposed work will significantly extend past work and examine a number of factors including the source of low energy particles (suprathermal versus thermal solar wind), upstream magnetic fluctuations (pre-existing versus self-excited fluctuations), and shock properties (Mach numbers, incident magnetic angles, etc.) to better understand these variabilities.

The proposal will combine state-of-the-art hybrid simulations (kinetic ions and fluid electrons) and MHD-PIC (MHD with kinetic ion feedback) simulations with in situ spacecraft measurements provided by ACE, Wind, and STEREO. We will examine how low-energy particles, magnetic fluctuations in the shock region, and shock properties in accelerating particles by numerical simulations for energetic particle acceleration and in situ observations. The outcome of this project will consist of the roles of those factors in the acceleration of charged particles at shocks and contribution to energetic particle variabilities close to the IP shocks.

Understanding energetic charged particles throughout the heliosphere is a long-standing problem and important task for heliophysics and space weather. Knowing how shocks accelerate particles and how that process depends on different physical factors are critical for us to further understand this basic process, and predict extreme acceleration in solar energetic particle events. This proposal addresses two NASA heliophysics objectives: Explore and characterize the physical processes in the space environment from the Sun to the heliopause and throughout the universe, and develop the knowledge and capability to detect and predict extreme conditions in space to protect life and society and to safeguard human and robotic explorers beyond Earth.

Heliophysics Guest Investigators – Open 2021
Abstracts of selected proposals
(NNH21ZDA001N-HGIO21)

Below are the abstracts of proposals selected for funding for the Heliophysics Guest Investigators – Open 2021 program. Principal Investigator (PI) name, institution, and proposal title are also included. Seventy- five (75) proposals were received in response to this opportunity. On December 16, 2021, twenty-four (24) proposals were selected for funding.
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Oleksiy Agapitov/University of California, Berkeley
Phase coherence of intense chorus type whistler waves: effects on resonant interaction with electrons

The Earth's radiation belts (RB) present a natural hazard to space exploration. The past decade has shown great progress in understanding the processes that drive RB dynamics and the crucial role of resonant electron interaction with whistler-mode waves for thie dynamics. However, there are still two essentially different concepts in competition for providing an accurate description of actual wave-particle interactions in the RB: (1) the quasi-linear diffusion theory (QLDT) assumes that electrons are continuously scattered through random numerous interactions with low-amplitude waves with a sufficiently broad spectrum. The main problem with the applicability of this concept is that observed whistler-mode waves are often highly coherent and reach sufficiently high amplitudes to violate the applicability criteria of the QLDT; (2) the models of nonlinear (NL) electron resonant interaction with highly coherent waves operate with principally non-diffusive phenomena as electron phase trapping and phase bunching. Models of NL wave-particle interaction predict a considerably more effective and rapid electron acceleration and scattering than the QLDT does. In fact, the observed long-term variations of relativistic electron fluxes are often well reproduced by the QL diffusion models, despite the presence of a significant population of very intense coherent waves that should in principle lead to a predominance of NL effects. This suggests that NL effects are often somewhat mitigated in the RB. The main goal of this project is to reveal wave properties that control the efficiency of NL wave-particle interaction and can contribute to the mitigation of NL resonant effects presumably leading to transition to much smaller interaction effects (i.e. to the QL model). These wave properties may well consist of the short time scale variations of wave amplitude, wave frequency, and wave phase often observed within or in-between chorus wave-packets and are rarely included in the existing models of wave-particle interaction.

The first objective of this project is to reveal characteristics of wave temporal phase, frequency, and amplitude variations for intense chorus waves in the radiation belts, i.e. to determine the typical time scales of chorus wave amplitude, frequency, coherence variations. Results of the first objective will be used for the construction of the realistic model of a chorus wavefield to be used for evaluations of the effects of these factors to nonlinear wave-particle interactions making use of the test-particle models. Thus, the second project objective is to reveal how the realistic wave phase, amplitude and frequency variations alter nonlinear electron interaction with chorus waves and to verify the level of perturbation, which releases the connection with the QL approximation. The third objective is to validate the criteria for the applicability of QL and NL approximation depending on geomagnetic conditions and local plasma characteristics.

The methodology of this objective consists of a combination of processing the Van Allen Probes and MMS wave observations (waveforms collected during minutes and hours; phase, amplitude, spectral processing of single- and multi-spacecraft VLF data), massive test particle simulations, and theoretical estimates.
This project is focused on the effects of realistic variations of wave phase and wave frequency on electron interaction with intense whistler waves (widespread through the entire heliosphere, including solar wind and planetary magnetospheres) and will shed new light onto the limits of applicability of NL and QL approaches to wave-particle interactions in the heliosphere and the important impact of this for the RB dynamics. Therefore, the project is relevant to NASA's Heliophysics' overarching goal and the specific objective: Explore and characterize the physical processes in the space environment from the Sun to the heliopause and throughout the universe.

Sofiane Bourouaine/Applied Physics Laboratory
On the origin of energetically-dominant sunward-propagating Alfvén waves in the solar wind

SCIENCE OBJECTIVES. We propose to conduct a statistical analysis using a large set of in-situ measurements of field and plasma data to answer the following scientific question: What are the sources and the nature of energetically-dominant Sunward Alfvén Waves (SAW) in the solar wind? To answer this question we aim to accomplish the following scientific goals: 1) Determine the occurrence of SAW and their characteristic scales versus heliocentric distance; 2) Determine how the existence of SAW is related to the type of solar-wind streams, magnetic polarity, magnetic field reversal, magnetic reconnection exhausts, and discontinuities; 3) Investigate the possibility of turbulent-generated SAW and study their turbulent multi-scale nature.

BACKGROUND. It is well known that Alfvénic fluctuations are observed to propagate primarily anti-sunward. The existence of sunward-propagating Alfvén waves was assumed to be rare in the solar wind. Here SAW refer to those solar wind intervals where sunward-propagating Alfvénic fluctuations are energetically dominant. Unlike outward-propagating Alfvén waves that are known to originate from the Sun, the dominant SAW are presumed to have their sources located in the solar wind. A limited number of periods with discrete SAW fluctuations have been investigated in previous studies. These studies have revealed distinct scenarios that might be associated with the generation of dominant SAW, such as the magnetic-field reversal (also called switchbacks), magnetic field connectivity to the earth bow-shock, and magnetic reconnection exhausts. On the other hand, studies based on high-resolution numerical simulations of imbalanced MHD turbulence with a net and sign-definite large-scale cross-helicity, have shown the existence of patchy regions with inverted sign of small-scale cross-helicity within the inertial range. These numerical results provide some insights that the observed SAW might originate from solar wind turbulence. Therefore, the focus of this proposal is to investigate the nature of these SAW to better understand the fundamental physics that govern the creation of these waves in the inner heliosphere and at heliocentric distances near and higher than 1 au.

METHODOLOGY. To statistically investigate the nature of the dominant SAW in the solar wind, we will use plasma and field data from multiple spacecraft such as WIND, ACE, Ulysses, Helios and SO. Using data from all these spacecraft will allow us to determine the occurrence and characteristic scales of these SAW in the inner heliosphere up to heliocentric distances of about 1 au and above. We will estimate the physical parameters associated with these SAW, such as the normalized cross-helicity, Walén coefficients, and plasma incompressibility. We then investigate how frequently these waves are produced. The classification of these observed SAW will be performed based on their relation to the observed plasma and field features. We will investigate a couple of possible physical features associated with the generation of these waves such as discontinuities, magnetic reconnection exhausts, magnetic field reversal, magnetic connectivity, and other possible transient events. Lastly, we will study the turbulent properties of these SAW using a technique based on conditioned correlation functions. This technique allows us to handle the patchy property of these waves and to investigate the role of turbulence in their origin and properties by comparing them with phenomenological models and advanced numerical simulations of MHD turbulence.

RELEVANCE. This project directly addresses one of the goals of WIND mission, e.g., "to Investigate basic plasma processes occurring in the near-Earth solar wind", and one of the four high-level science goals of the Heliophysics decadal survey, e.g., Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe.

Douglas Braun/NorthWest Research Associates, Inc.
The Subsurface Nature of Supergranulation and Active-region Flows as Inferred from Probabilistic Inversions of Ensemble Averaged Travel-time Measurements

The investigators will use observations from the Helioseismic and Magnetic Imager (HMI) on board the Solar Dynamics Observatory to characterize the subsurface properties of supergranular (SG) and active-region (AR) flows. The team will make use of ensemble averaging of the helioseismic travel-time maps of many thousands of targets (SGs or ARs) to overcome noise. The travel-time maps are obtained by applying helioseismic holography to HMI Dopplergrams. Inversion methods based on Bayesian theory, exploited in other contexts including astrophysics, will be applied to averages of travel-time differences to infer subsurface flows. These methods are novel to helioseismology and are expected to provide improved solutions with more realistic error estimation. The project will form the main component of a PhD dissertation for a graduate student.

Recent analyses of time-distance measurements suggest very fast (up to 700 m/s) and shallow (confined to within a few Mm below the photosphere) supergranular flows. This represents a new paradigm for the subsurface structure of SGs. However, these controversial results remain largely unconfirmed. Recent forward modeling by the team using holography measurements suggest that horizontal flows from SGs peak in strength at greater depths (7-10 Mm below the surface) and are more consistent with results from recent MHD simulations. To ascertain the subsurface structure of SG flows the team will apply probabilistic inversion methods, specifically adopted and optimized for this problem, to existing ensemble averages of nearly 60,0000 SGs. A similar quantity of additional holography measurements, applied to existing HMI Dopplergrams, will sample an entire solar cycle. The goal is to probe the subsurface variations among SG subsamples with different surface properties (e.g. strength of inflow), time, and proximity to magnetic fields.

The detection of flows with amplitudes of order 10-30 m/s and converging towards active regions was an early discovery made from studies employing low-resolution (~15 degrees) ring-diagram methods. However, their deeper structure and its variation with properties of the associated regions have remained elusive. For this component of the work, an existing set of more than 5000 high-resolution (~1 degree) holography measurements of AR flows spanning the HMI mission lifetime will be employed, with additional measurements planned. Probabilistic inversions of the ensemble averages will be carried out in a fashion similar to those of SGs. Inversion tasks for both targets will include testing a variety of parametrized flow formulations and making robust error estimates. Existing fully convective MHD simulations of sunspots and ARs will provide guidance as to the treatment or removal of data compromised by strong fields in sunspot umbrae and penumbrae. The result will be a determination of the three-dimensional flow structure of the averaged AR, as well as flows for subsets of the data corresponding to different magnetic flux levels and evolutionary stages.

Characterizing and understanding the nature of supergranular and active-region flows through the methods proposed in this project are critical to achieving the goals of HMI and the SDO Mission. The primary goal of HMI (see http://hmi.stanford.edu/Description/HMI_Overview.html) is to study the origin of solar variability and to characterize the Sun's interior and the various components of magnetic activity. Specifically, this broad goal is achieved through exploring various interlinked processes including the dynamics of the convection zone and the origin and evolution of ARs. Empirical inferences of the subsurface structure of flows proposed here will directly constrain models of the physics of supergranular convection (characterizing the dynamics of the solar interior) and flows around active regions (characterizing the evolution of magnetic activity).

Radoslav Bucik/Southwest Research Institute
Understanding the Origin of 3He-rich Solar Energetic Particles using in-situ and Remote Imaging Observations

Science: The objective of this study is to determine the physical and phenomenological processes in solar sources that organize the unusual enhancements of 3He and heavy ions in 3He-rich solar energetic particle (SEP) events. To achieve this objective, we answer the following focused science question: How are the elemental composition and energy spectra of 3He-rich SEPs influenced by the (1) flare emission structure; (2) type of the associated coronal motion; (3) the underlying photospheric field configuration; and (4) temporal evolution of magnetic flux?

Motivation: 3He-rich SEPs show enormous enhancements of rare species such as 3He and ultra-heavy elements (e.g., Pb) by factors up to ~10,000 above the nominal coronal abundances. Anomalous elemental composition of 3He-rich SEPs is believed to indicate a unique acceleration mechanism operating in solar flares sites. Although they were discovered in the early 1960s, 3He-rich SEPs are still poorly understood. One reason is the difficulty of pinpointing and resolving the small source regions of these events. Significant advances in understanding 3He events were provided by ACE and SOHO instruments in the 1990s, albeit with a limited spatial and temporal resolution of SOHO images. Several later studies reported the association of 3He events with jets, suggesting acceleration via magnetic reconnection involving field lines open to the interplanetary space. More recent work, based on STEREO and SDO observations, indicated that the jet triggering mechanism (emerging flux, mini-filament eruption) and magnetic field environment (coronal holes, sunspots) appear to be related to 3He-rich SEP production.

Data and Methodology: We make significant progress toward answering our proposed science question using comprehensive in situ and remote-sensing analyses that utilize four active Heliophysics missions, namely, ACE, Wind, STEREO, and SDO. In particular, we use 1 au energetic particle data in conjunction with radio and imaging observations of source flare and photospheric field at unprecedented high resolution. For example, the cadence of SDO images is at least 60 times higher than SOHO images. The solar sources are identified using the temporal coincidence between the EUV brightening and type III radio bursts that occur around the estimated ion solar release time. We specify the flare morphology (e.g., helical jets) and type of coronal motions (unwinding jets, large-scale propagating waves) in the solar sources. We examine the photospheric field configuration (a coronal hole, sunspot) and evolution (e.g., buildup time). Furthermore, the jet and wave characteristics (e.g., angular and propagation speeds) and photospheric field parameters (e.g., gradient, helicity) obtained from the Space weather HMI Active Region Patch (SHARP) database are analyzed for their coupling with elemental composition and spectral indices. Our proposed study is timely not only because such an unprecedented set of measurements have recently become available, but also because the results from this work complement and advance the scientific understanding of 3He-rich SEPs observed closer to the Sun by the recently launched Parker Solar Probe and Solar Orbiter.

Relevance: Our investigation is highly relevant to the goals of the missions whose data are used. It is specifically relevant to two major areas of ACE science: (1) The elemental and isotopic composition of matter, and (4) Particle acceleration and transport in nature.

It is also relevant to the SDO science question: What magnetic field configuration leads to the flares that produce energetic particles and radiation? Furthermore, it responds directly to two of the high-level science goals from the Heliophysics Decadal survey: (1) Determine the origins of the Sun s activity and predict the variations in the space environment, and (4) Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe.

Federico Fraternale/University of Alabama in Huntsville
Cosmic rays in the turbulent heliosheath and very local interstellar medium

Background and science objectives.
Voyager 1 and 2 spacecraft (V1, V2) have crossed the heliopause (HP) and are currently exploring the Very Local Interstellar Medium (VLISM) providing us with unique in situ data out to ~152 au (V1) and ~126 au (V2) from the Sun. Recent observations confirm the complex dynamics of the solar wind (SW) - VLISM interaction and reveal the fundamental properties of magnetic field (B) fluctuations in the interstellar plasma ahead of the HP. Turbulence at 30 au from the HP is still affected by the solar-induced disturbances, including shock waves and quasi-periodic fluctuations. Turbulence as observed by Voyagers is characterized by low-intensity, compressible fluctuations on spatial scales ranging from ~10 au to ~1000 km. Compressible and Alfvenic turbulence coexist with prominent coherent structures in the inner heliosheath (IHS). Anisotropy of Galactic cosmic ray (GCR) proton fluxes is typical of the VLSIM. Although it has not been observed for GCR electrons, they exhibit distinct quasiperiodic oscillations. Their comparison with the observed scales of turbulence suggests that such oscillations are physically significant and can provide further insights into the properties of turbulence. Similar features can be detected also in the IHS, where the turbulence is stronger than in the VLSIM. Turbulence is known to affect the GCR transport through resonant and non-resonant interactions, and plays a fundamental role in GCR scattering and isotropization. An accurate description of the scaling and anisotropy of turbulence is essential for the derivation of GCR transport coefficients. Since no theory of turbulence in the IHS and VLISM has been developed yet, our objective is to use observational data to establish relations between turbulence and GCR fluxes in the outer heliosphere and VLISM. We will (i) carry out a systematic frequency-space analysis of the GCR electron and proton rates measured by Voyagers in the VLISM, IHS, and distant SW; (ii) identify the patterns and dominant periodicities, and cross-correlate them with the turbulence spectra; and (iii) compute GCR diffusion coefficients using realistic turbulence properties constrained by in situ observations.

Mission data and methodologies.
We will use high resolution (48s) magnetic field data from the V1 and V2 MAG experiment, and GCR data from the Cosmic Ray Subsystem (CRS), in the energy ranges of 3-110 MeV for electrons and 3-500 MeV for protons. These data are publicly available at NASA's Space Physics Data Facility (SPDF). GCR time series and MAG data are affected by statistical noise and data gaps of several hours per day, which makes frequency-space analysis difficult. Advanced spectral analysis techniques (wavelet transform, empirical mode decomposition, compressive sampling, Lomb-Scargle

periodogram) have been applied to determine magnetic turbulence spectra. These techniques will also be used to analyze GCR data. Special methods of pattern recognition will also be developed to discriminate physical fluctuations from instrumental artifacts. Monte Carlo tests based on synthetic turbulence data sets will be used to assess the statistical confidence level. The cross-spectrum of turbulence and GCR rates will be then investigated. Ultimately, the GCR diffusion coefficients will be derived in the theoretical framework of quasilinear and non-linear guiding center theories.

Relevance. This project will allow us to perform a coordinated analysis of CRS and MAG data, identify physical processes affecting the GCR transport through the heliospheric boundary, and in this way maximize the scientific return from the Voyager mission. The proposal fits the following objective of the Heliophysics Research Program: Explore and characterize the physical processes in the space environment from the Sun to the heliopause and throughout the universe .

Arthur Hull/University of California at Berkeley
The scale dependency of field-aligned currents, energy fluxes, and dissipation rates in the near-Earth magnetotail

Field-aligned currents in the near-Earth magnetotail play a crucial role in coupling the reconnection driven transport of momentum and energy from the magnetosphere to the ionosphere. Though considerable progress has been made in understanding currents and their importance to transport processes at larger scales in the tail, the nature and relative importance of field-aligned currents, and association with energy flow and dissipation down to kinetic scales is not fully understood. This is a proposal to study the scale dependency of field-aligned currents, energy flux (wave and particle), and dissipation rates (J dot E) in the near Earth magnetotail. In particular the following interrelated questions will be addressed:

1. What is the distribution of field-aligned current, Poynting flux and particle energy flux in the near earth magnetotail as a function of scale?

2. How does the nature of field-aligned current and Poynting flux vary as a function of scale?

3. How does the population of current carriers and the energized plasmas that carry energy flux vary as a function of scale?

4. What are the contributions to energy dissipation (J dot E) associated with the field-aligned currents as a function of scale?

The science goals will be achieved via case studies and statistical analysis of plasma and field observations from the Magnetospheric Multiscale (MMS) mission.
The data set from MMS is unique in that it is the only in-situ mission designed to date capable of routinely providing multipoint measurements of the plasma and fields with the requisite time resolution to accurately assess field-aligned currents, and associated energy

flow and dissipation rates down to kinetic scales. We will take advantage of the multipoint capabilities to determine the scales (via interferometry) of current systems, energy fluxes, and dissipation rates observed and assess their geometry and nature. The current properties will be compared with observed features in the high-time-resolution electron and ion distribution functions and moments to assess the current carriers and physical makeup of the currents observed. The long duration high-time resolution burst plasma, electric and magnetic measurements will be used to evaluate contributions to currents, Poynting fluxes, plasma energy flux, and dissipation rates down to kinetic scales. Auxiliary data (e.g., from Omniweb) will also be used as needed for contextual purposes, such as AE index, as a measure of magnetospheric activity.

Relevance:
This proposal addresses fundamental questions regarding field-aligned currents in the near-Earth magnetotail. Field-aligned currents are essential in coupling the reconnection driven transport of momentum and energy from the magnetosphere to the ionosphere. The field-aligned currents and associated energy flow and dissipation occur over multiple scales, which to date are not fully understood. Understanding these questions will provide key insight into characteristic scales and partitioning of different contributions to current in the near Earth magnetotail, and hence their relative importance to coupling, energy transport and dissipation in the magnetosphere-ionospheric system. These results will have broader application to magnetized planets (e.g., Mercury, Jupiter, and Saturn), where field-aligned currents have been observed and thus similar transport and dissipative process can occur. Thus, the proposed goals are directly relevant to the NASA's overarching goal ``to understand the Sun and its interactions with the Earth and the Solar System, including space weather'' and key objective to ``explore and characterize the physical processes in the space environment from the Sun to the heliopause and throughout the universe''.

Jay Johnson/Andrews University
Magnetosphere-Ionosphere coupling of small scale structures

Science goals and objectives:
Small scale (< 1degree in latitude and longitude) upward field-aligned currents (FACs) and electron precipitation are commonly observed in the ionosphere. At the magnetopause boundary layer, the large scale FAC is believed to be driven by the velocity shear. However, high velocity shear can also lead to Kelvin-Helmholtz Instability (KHI), which can drive small scale FACs that superimpose on the large scale FACs. In the upward FAC regions, whenever the electron density in the magnetosphere is too low to carry the currents, a quasi-static parallel potential drop develops to draw more electrons downward, which are observed as monoenergetic electrons. Analogous to the boundary layer, in the magnetotail, velocity shear between the fast flows and the surrounding plasma can also lead to the development of KH vortices and small scale FACs. Coupling to the ionosphere can be different depending on whether the flows are stronger during the expansion phase or weaker during steady magnetospheric convection.

The main goals of this project are to determine the characteristics of the small scale FACs and electron precipitation that originate from the boundary layer and nightside closed field. The proposed work will address the following science questions that are fundamental to the small-scale magnetosphere ionosphere (M-I) coupling: 1. What are the characteristics of upward field-aligned currents in the boundary layer associated with velocity shear and/or Kelvin-Helmholtz vortices? 2. What are the characteristics of the upward small-scale currents generated by the fast flows in the magnetotail and how do they differ from boundary layer currents? and 3. To what extent can the boundary layer structures be inferred from ionospheric observations?

Mission data to be used:
We will use MMS (primary), THEMIS, Cluster and Geotail observations of the magnetospheric and boundary layer electric and magnetic fields, fast flows, plasma pressure, density, and velocity and KH vortices. In the ionosphere, we will use FAST, Swarm, and DMSP satellites to provide observations of particle precipitation and FACs. DMSP SSUSI and THEMIS All Sky Imagers (ASI) can provide images of aurora, from which more global picture of upward FACs and electron precipitation can be inferred.

Methododogy:
We will analyze data in the context of theoretical models that describe small scale field-aligned current generation by KH vortices. These models will include a simple analytic model that couples a KH driver with the ionosphere. We will also use the Open GGCM MHD code to simulate KH vortices and their associated FACs. Observations will be compared and interpreted with the theory and models.

Relevance to NASA programs:
The goals of the proposed study will go beyond MMS mission goals, utilizing the constellation to probe kinetic processes in the boundary layer and their mapping to the ionosphere. The proposed objectives are relevant to the Heliophysics goal outlined in B.1: Explore and characterize the physical processes in the space environment from the Sun to the heliopause and throughout the universe.

Sylvain Korzennik/Smithsonian Astrophysical Observatory
Global Helioseismology: State of the Art Derivations of the Dynamics and Structure of the Solar Interior from HMI Observations.

The scientific goals of this proposal are to derive state-of-the-art inversions for the solar internal rotation, the internal solar structure, and their variation with solar activity using both the best possible inversion techniques and optimal fitting methodologies, based on new and past HMI observations.

The technical goals of this proposal are to (a) apply a state-of-the-art fitting methodology to new HMI observations and (b) further improve and validate these methodology improvements. This method provides an invaluable alternative to the standard global helioseismic reduction pipe-line, known to produce biased estimates when using MDI and HMI observations.

The Stanford reduction pipe-line of HMI is now capable of processing the intensity as well as the velocity images. Fitting co-eval intensity and velocity data will further validate this methodology, as indicated by the results of fitting one year of HMI intensity data.

This proposal will allow us not only to continue to carry out the fitting of HMI velocity observations as they become available, but catch up with the backlog of HMI intensity observations as they get processed by Stanford. Extending this to all of HMI observations will be key to validate the changes in asymmetry that are seen in some fitting results of the velocity and less so in others.

The resulting p-modes tables, as well as these produced by the Stanford group will in turn be inverted, using the most advanced inversions techniques available, to continue the precise monitoring of the changes of the solar interior structure and dynamics. Several inversion techniques will be developed, validated and used to further improve the spatial and temporal resolution of the traditional methods, and special attention will be paid to avoid inverting noise as solar features by assessing not just how the random noise propagates, but how large the residual systematics still are.

The proposed work will directly contribute to our understanding of the origins of the Sun's activity (key science goal #1 of the Heliophysics Decadal Survey) and further key science goal #4 by contributing to our understanding of the solar dynamo, and therefore similar dynamos.

This proposal will draw extensively from the data set produced by HMI on SDO, a data set that will be complemented by simultaneous ground-based observations acquired by the NSF-funded GONG project.

Enrico Landi/University of Michigan
Monitoring active region coronal magnetic fields over the solar cycle with Hinode/EIS

SCIENCE GOALS: The magnetic field of the solar corona is one of the most critical parameters in solar physics, as it lies at the core of most manifestations of coronal physics and of the interactions between the Sun and its planetary system. Despite its importance, measurements of the magnetic field of the solar corona have been elusive, due to the weakness of its signatures in remote sensing observations. While upcoming facilities like DKIST and UCoMP will provide us with spectropolarimetric measurements of coronal magnetic fields at the limb, few measurements are available on the disk, and no measurements have been systematically carried out to understand the effect of the solar cycle on the coronal magnetic field. In this investigation, we will apply a novel diagnostic technique that measures the magnetic field strength in active regions utilizing a few Fe X

and Fe XI spectral lines commonly observed by the Hinode/EIS high resolution spectrometer. We will apply this technique to EIS observations from 2007 to date, and compare measurements with predictions of the AWSoM global 3D MHD model of the solar corona, in order to answer the following science questions:
1 - Does the solar cycle affect the strength of coronal magnetic field in active regions, and to what extent;
2 - Does solar magnetic field strength and morphology correlate with activity (e.g. solar flares, CMEs) in active regions;
3 - How does the coronal magnetic field of an active region evolve during the life of the active region;
4 - Can global models correctly predict the strength of active region magnetic fields and their evolution.

METHODOLOGY: We will utilize Hinode/EIS spectra of solar active regions on the disk and at the limb, to apply this novel technique (developed by the PI) that allows the measurement of the coronal magnetic field from a handful of Fe X lines commonly observed by the Hinode/EIS spectrometer. Measurements will be extended to the entire operational life of the EIS spectrometer, from 2007 to date (and beyond, if the instrument does not fail) covering the full solar cycle 24 and the beginning of cycle 25. Results will be compared to predictions from the global 3D MHD model (AWSoM). Photospheric magnetic field measurements will be used as boundary conditions for AWSoM, while X-ray and EUV images from multiple instruments will be used as context images for the EIS field of view.

INSTRUMENT DATA: Hinode: EIS, XRT; SDO: AIA, HMI; STEREO: EUVI; SoHO: EIT, MDI; GONG

RELEVANCE: The coronal magnetic field is at the heart of the physics of the solar corona and of Space Weather events (flares, CMEs), but its measurements have been very difficult. The novel diagnostic technique we will utilize opens an entire new window on the coronal magnetic field of active regions, which utilizes a vast amount of data from the EIS spectrometer available in the EIS archive and waiting to be analyzed. This investigation thus will allow us to directly address, in a completely novel way, the science objectives of "Exploring and characterizing the physical processes in the space environment" at the Sun, and "Advance out understanding of the Sun's activity".

Jiang Liu/IGPP UCLA
Field-Aligned Currents of the Dipolarizing Flux Bundles and the Associated Plasma Disturbance: Understanding the Formation and Asymmetry of Wedgelets

During substorms, the magnetotail s configurational change is carried out by dipolarizing flux bundles (DFBs). A DFB is a 0.5-3 RE-wide flux tube with more dipolar magnetic field than the background. After being generated by reconnection around 20-30 RE downtail, DFBs propagate earthward in the form of bursty bulk flows. The leading edge of a DFB is characterized by a steep enhancement of Bz (in GSM) known as a dipolarization front (DF).

Previous studies showed that each DFB carries a pair of Region-1-sense field-aligned currents (FACs) and a pair of Region-2-sense FACs (Region-1/2 sense indicate the directions of the FAC pair). This configuration resembles that of a substorm current wedge (SCW), but of a much smaller scale. Because most DFBs appear during substorms, DFBs FACs are most likely related to the SCW. They may serve as wedgelets that collectively form an SCW. Because the SCW is the most important current system of a substorm and reflects the transport and conversion of magnetic energy during a substorm, knowledge about DFBs FACs is crucial for under-standing how substorms function.

Science Goal

To collectively form an SCW, the net FAC of all DFBs in the dawn sector of the magnetotail must be downward to the ionosphere and equal to that in the dusk sector, which must be upward. Previous studies showed that this configuration is possible a typical late-stage DFB in the dawn (dusk) sector carries more downward (upward) FAC than upward (downward) FAC. Knowledge of the source of this asymmetry is crucial for the validity of the wedgelet scenario. This knowledge is also important for understanding the magnetosphere from a system science point of view because the asymmetry and dawn-dusk current closure can only be achieved by the interaction between meso- and large-scale structures in the same system. We propose to achieve this knowledge by answering the following specific questions:

1. Is the DFB-related plasma pressure disturbance asymmetric in the way consistent with coupling of large- and meso-scale pressure distribution, and thus the asymmetric FACs?

2. Does the flow perturbation around the dipolarization front consistent with asymmetric FAC driving inside the DF layer?

3. Are the DFBs FACs also asymmetric in their early stage? Are their related pressure distribution consistent with their FACs?

-- Methodology

We will rely on NASA s THEMIS and MMS missions to answer the proposed questions. After years of operation, both missions have collected massive data allowing comprehensive statistical studies. During the tail phases of the missions, THEMIS has apogees near the inner edge of the plasma sheet, suitable for observing late-stage DFBs and MMS apogee is at 20-30 RE downtail, where early-stage DFBs appear. THEMIS and MMS are equipped with high-quality magnetometer and electric field and particle instruments, allowing us to infer DFB-related current density, plasma pressure and flow. Statistical studies on these values will answer the proposed questions.

-- Relevance to the call.

All data our proposal uses are from currently operating NASA HSO missions. Our proposal is relevant to the goals of the Heliophysics Decadal Survey (explore and characterize the physical processes in the space environment).

Wei Liu/Bay Area Environmental Research Institute
Global EUV Waves and Their Interaction with Coronal Structures: Multi-wavelength Analysis and MHD Modeling

Motivation and Significance: Global extreme-ultraviolet (EUV) waves, discovered by SOHO/EIT (thus often called EIT wave), are the most spectacular traveling disturbances in the magnetized solar atmosphere. Morphologically analogous to terrestrial tsunamis, they typically appear as expanding annular EUV enhancements traversing the global corona. The importance of EIT waves lies in a multitude of aspects: (1) They are associated with space weather driving eruptions, involving coronal mass ejections (CMEs) and flares, and can be the low-corona signatures of CME-driven shocks. (2) They serve as the linkage among a variety of solar activity, e.g., with their role in energy transport across the global corona, their impact on the coronal plasma and magnetic field conditions, and their potential triggering of remote, sympathetic flares. (3) Like any propagating waves, EIT waves can also provide diagnostics for their medium, i.e., the large-scale corona. However, the area of global coronal seismology has been significantly under-explored, mainly because the physical properties of EIT waves were not well understood.

Science Goals and Objectives: We propose an investigation with an overarching goal to characterize the physical properties of global EUV waves, in an effort to advance our understanding of their role in solar eruptions and exploit their diagnostic potential for global coronal seismology. Our specific science objectives are: (1) Characterize the propagation properties of EIT waves and specifically understand their role in energy transport; (2) Characterize their behaviors upon interaction with coronal structures, including reflection, transmission, and refraction; (3) Characterize their impact on the coronal plasma and magnetic field, including their potential role in triggering sympathetic flares.

Primary Mission Data: (1) We will primarily use multi-passband EUV data from SDO/AIA, and whenever available, STEREO/EUVI of identified global EUV wave events. (2) SDO/HMI and supplementary data will be used for modeling the coronal magnetic field (by extrapolation) and as inputs to data-driven MHD modeling.

Data Analysis Methodology and Coordinated Modeling: We will adopt a two- pronged approach with a focus on observational analysis of satellite data supported by numerical modeling using a state-of-the-art MHD code. Our key tasks include: (1) Systematic survey throughout the SDO mission of EIT waves that show clear sign of interaction with various coronal structures, including active regions, coronal holes, and coronal cavities. (2) Detailed analysis of multi-wavelength observations of those identified events. (3) Advanced 3D MHD simulations of selected EIT wave events and synthesis of observables in comparison with data analysis results. We will use the Alfven Wave Solar

Model (AWSoM), a data-driven global MHD model, together with the Eruptive Event Generator Gibson-Low (EEGGL) to model solar eruptions that drive EIT waves. The novelty of the proposed research lies in the fact that no such systematic study characterizing EIT waves and their interaction with coronal structures has previously been carried out.

Relevance: This proposal directly addresses two of the three combined objectives of the Heliophysics: (1) Explore and characterize the physical processes in the space environment from the Sun to the heliopause and throughout the universe , as global EUV waves are manifestations of fast-mode waves, a basic form of MHD waves ubiquitously found in space and astrophysical plasmas, and (2) Advance our understanding of the Sun s activity... , as global EUV waves are integral parts of solar eruptions involving CMEs and flares.

Larry Lyons/UCLA
Coordinated THEMIS All-Sky-Imager, Ground Magnetometer, and Radar evaluation of Flow Channel Control of Substorm Expansion Development

Due to the direct connection of the ionosphere and magnetosphere, examination of the aurora, current, and flows in the auroral ionosphere opens a 2-D window into dynamics along plasma sheet field lines, providing extensive information that cannot be obtained from sparse spacecraft. A major advance obtained by the THEMIS all-sky imagers (ASIs) was the inference that meso-scale flows impinging on the equatorial portion of the auroral oval lead to substorm onset, an inference supported by a few case studies of flows. These meso-scale flow channels correspond to plasma sheet flow bursts that carry lower flux-tube integrated entropy than the surrounding plasma into the inner, transition region of the plasma sheet. There they lead to an instability that appears as growing waves that have become referred to as beading, which demarcates substorm onset and is observed along an east-west oriented arc and leads to auroral breakup. However, onset is only the initiation of a substorm. The ensuing substorm expansion phase can be brief, lasting only a few minutes, or much longer, lasting up to an hour or so. Furthermore, substorms expansion phase activity can be narrow or broad (several hrs in MLT) in longitude and can lead to, or not lead to, large ground magnetic perturbations. Both the spatial extent, the duration, and the associated ground magnetic field changes are crucial to the Space Weather effects of a substorm, so that determinations of what controls these features are crucial outstanding questions of which little is currently known. Fundamental to these questions is the observation that auroral beading occurs along an east-west oriented auroral arc, not along an auroral streamer (the auroral signature of a flow channel), and that the beading spreads azimuthally along this east-west arc. The dominant cause of azimuthal motion within the inner plasma sheet is magnetic drift. Recent results from the Rice Convection Model show that the low entropy plasma within a flow burst spreads azimuthally via the energy-dependent magnetic drift and background convection distorted by Region 2 field-aligned currents (also driven by magnetic drift), offering a plausible explanation for the azimuthally expanding substorm onset instability seen as auroral beading. Furthermore, this spreading is associated with development of N-S electric fields within the ionosphere, and the modeled electric fields having a significant, observable dawn-dusk latitudinal asymmetry with respect to the expected latitude of onset.

We will use the THEMIS ASI and associated ground magnetometer network in coordination with the SuperDARN and Poker Flat Incoherent radar to address fundamental questions concerning the substorm issues described above: 1. Do we consistently see the flows heading toward the auroral onset location soon prior to onset as expected from the auroral observations? 2. Is the azimuthal expansion of the onset auroral beading, including the extent of this expansion, associated with the azimuthally directed flows as expected from the model diversion of flows when they reach the inner plasma sheet? 3. Can we relate significant broadenings of the longitudinal extent of expansion phase activity and concurrent prolonging of activity to a second (or more) streamer and associated flow channel occurring after onset, including streamers at MLTs adjacent to an ongoing expansion and flow channels impinging on the auroral westward traveling surge? 4. How do the substorm auroral features such as auroral streamers and auroral beading relate to whether the largest ground magnetic H depressions occur and how broadly distributed are the large depressions?

This proposal combines THEMIS ASI and ground magnetic field data with ground radar observations to directly address fundamental aspects of Decadal Survey goal #2: the dynamics and coupling of Earth s magnetosphere and ionosphere along plasma sheet/auroral oval field lines and their response to solar inputs.

Hiroshi Matsui/University of New Hampshire
A multi-instrument study of dipolarization events accompanied by large electric fields in the inner magnetosphere

A dipolarization of the geomagnetic field occurs during some geomagnetic activities, such as substorms. Since magnetic field lines move during these events, electric field variations are also expected. These dipolarization events are considered to originate from reconnection and have been extensively studied in the magnetotail. For example, large Hall electric fields are generated by the pressure gradient around the dipolariation front. When these dipolarization events propagate toward the inner magnetosphere, they might be affected by particles' gradient B/curvature drifts due to spatial variations of the background magnetic field so that different configurations from the magnetotail are expected. In a previously-reported dipolarization event caused by these drifts, large electric fields were measured. We therefore focus here on dipolarization events accompanied by large electric fields in the inner magnetosphere using Magnetospheric Multiscale (MMS) mission data. Our objective is to study spatial distributions of these events and their physical properties. We address the following three science questions: 1. What are the characteristics of dipolarization events accompanied by Hall terms? 2. What are the characteristics of dipolarization events affected by gradient B/curvature drifts? 3. What are the statistical properties of dipolarization events in the inner magnetosphere? The background magnetic field strength significantly changes with radial distance from the Earth and so do the plasma parameters. The physical properties of dipolarization events in the inner magnetosphere could thus be different from those in the magnetotail.

Examination of this topic advances magnetospheric physics because dipolarization events are a common phenomenon in the nightside magnetosphere. In addition, this study contributes to further understanding the dynamics of the ring current and magnetosphere-ionosphere coupling. Dipolarization events have often been examined using magnetic field and energetic particle data. One unique feature of this study is to examine these events with high-time resolution data from MMS, including electric fields and magnetic currents. It is suitable to examine the above topic now because lots of data have been accumulated since MMS launch six years ago. As mentioned, we examine MMS data in this study. Magnetic fields, electric fields, and energetic particles are a primary data set. In addition, we examine upper hybrid frequency, spacecraft potential, and low-energy particles, when available. Interplanetary and geomagnetic conditions are monitored by OMNI data and geomagnetic indices, such as AE, Kp, and Dst indices, respectively. We apply the momentum equation and the generalized Ohm's law to the MMS data set to investigate physical properties of events. Since MMS consists of four spacecraft, we introduce multiple spacecraft data analysis such as the curlometer technique and the timing analysis. The volumetric tensor is also calculated to check whether the inter-spacecraft configuration is appropriate to use the above techniques. If not ideal, we directly compare two spacecraft data to estimate currents. The timing analysis is replaced by the minimum variance analysis. This study is relevant to the goals of the MMS mission in terms of investigating dipolarization events, which are consequences of the magnetotail reconnection. This study also contributes to the Heliophysics overarching goal to understand the Sun and its interactions with the Earth and the Solar System, including space weather. The proposal is related to one of the objectives of the program: Advance our understanding of the Sun's activity, and the connections between solar variability and Earth and planetary space environments, the outer reaches of our solar system, and the interstellar medium.

Karin Muglach/Catholic University of America
Understanding filament channel formation: a new observational approach

Understanding filament channel formation: a new observational approach

Science Goals and Objectives:

Coronal mass ejections (CMEs) and flares are large scale eruptive events that are among the most studied topics in solar physics due to their fundamental role in the release of energy, mass and magnetic field which can impact the Earth environment. A key characteristic of these eruptive events is the presence of a region of sheared or twisted magnetic field often containing a solar filament and thus known as the filament channel. Understanding these regions is an essential component of understanding the ultimate origin of solar eruptive events.

Solar filaments are structures consisting of cool dense plasma situated in the hot corona. They are visible in many chromospheric lines (e.g. H alpha) and can also be seen in some coronal lines as dark absorption features on the solar disk. The plasma is assumed to be connected to the magnetic field which forms the filament channel.

Photospheric line-of-sight magnetograms show that filaments always overlie a polarity inversion line (PIL), a location where the line-of-sight magnetic field is zero and has opposite polarity at both sides of the PIL. Using the chromospheric and coronal absorption structures as a proxy for the filament magnetic field one can find that these structures are almost parallel to the PIL, unlike magnetic field lines that connect the opposite polarities of active regions (ARs) which are mostly perpendicular to the PIL. Therefore, filaments represent magnetic structures that strongly deviate from the potential magnetic field configuration and thus can store magnetic energy that is released in eruptive events like flares and CMEs.

The key question we will address in the proposed work is: How do these filament channels form on the Sun? We will address this question by adding to the extremely limited number of observational studies of filament channel formation where we start from an unsheared state of the magnetic field to the appearance of a filament.

Data and Methods:

We will use an observational approach, primarily using SDO and STEREO data, complemented by ground-based H alpha data.

We will survey the data to identify cases in which we can observe the complete history of the filament channel formation in a variety of environments. Once we have identified cases of filament formation we will determine the evolution of the magnetic field and measure the photospheric flow field using three different algorithms. Two of these algorithms are new and will allow to accurately characterize the photospheric flow fields and the transport of magnetic flux by tracking individual magnetic flux patches. This will allow us to categorize the flow and flux evolution according to currently existing filament channel formation mechanisms.

Relevance:

The results of this study will provide fundamental information on what observed processes are involved when a filament channel forms. They can be used as a guideline for numerical models of filament channel formation.

This study is therefore directly relevant to NASA's science goals as identified in the Heliophysics Decadal Survey, specifically: ``1.~Determine the origins of the Sun's activity and predict the variations in the space environment" and ``4.~Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe."

This work will also address one of SDO's Mission Science Goal, "How does magnetic reconnection on small scales reorganize the large-scale field topology and current systems?" and "What magnetic field configurations lead to the CMEs, filament eruptions, and flares that produce energetic particles and radiation?"

Mitsuo Oka/University of California Berkeley
Particle Acceleration and Power-Law Spectra in Earth s Plasma Environment

Particles are accelerated to very high, non-thermal energies in many space, solar, and astrophysical plasma environments. Accelerated particles often form a power-law energy spectrum, but it is still unclear why power-laws are formed, how the power-law index (slope) depends on the plasma conditions, and ultimately how particles are accelerated. Of all the plasma environments, Earth s plasma environment is special in a sense that in-situ measurements are readily available and the particle energy spectrum can be obtained directly without the complexities remote-sensing measurements typically have. Furthermore, many models of particle acceleration involve fundamental plasma processes such as shocks and magnetic reconnection, and in the near-Earth environment both shock acceleration and reconnection-associated acceleration can be studied in-situ.

Thus, this proposal aims to advance our understanding of particle acceleration by focusing on Earth s plasma environment and further explorer the properties of power-law spectrum. More specifically, this proposal addresses the following science questions:

1. How often are power-law forms present in ion and electron energy spectra in Earth s plasma environment such as the bow shock and magnetotail, and what are the typical values of the power-law index ´?
2. What plasma conditions control the power-law index ´ in Earth s plasma environment?

To address these science questions, this proposed project will take the large amount of data obtained by NASA s MMS spacecraft and perform a systematic, statistical study. MMS has an advantage of covering a wide range of particle energy with its multiple instruments and their data are well calibrated. To characterize the particle energy spectra, a combination of different analytical forms of spectrum will be used to fit the data.

This proposal addresses an important science question regarding the fundamental plasma processes such as shocks and magnetic reconnection. As such, this project directly addresses one of the overarching goals of Heliophysics Research Program, i.e., Explore and characterize the physical processes in the space environment from the Sun to the heliopause and throughout the universe.

Denny Oliveira/University of Maryland, Baltimore County
Assessing interplanetary shock-induced dB/dt variations controlled by impact angles

Geomagnetically induced currents (GICs) caused by space weather pose serious threats to power transmission infrastructure. One of the main proxies to assess GIC impacts is the temporal variation of the ground magnetic field (dB/dt). At high latitudes, it is well known and understood that intense GICs are usually caused by magnetic storms. However, at lower latitudes, including sub-auroral regions, the main drivers of strong dB/dt variations are named interplanetary shocks (IPSs). The IPS impact angle, defined as the angle between the shock normal and the Sun-Earth line, has been shown to be a very important factor that controls the subsequent geomagnetic activity. Several modeling and experimental works show that fast, frontal shocks are more geoeffective. However, there have been limited studies that explicitly connect dB/dt variations with shock impact angles. Most numerical simulations use frontal impact angles as simple parameterizations, not addressing the complexity of inclined shocks. Their consequences to ground dB/dt variations at shock onset and substorm-like events have not been extensively addressed yet (less than 10% of shocks have impact angles smaller than 20o, which indicates that modeling works conducted so far may have been significantly simplified). Our work plans to rectify these limitations and correct prior non-applicable assumptions, thus improving our understanding of dB/dt variations by the majority of the shocks that impact the magnetosphere. We then plan to focus on answering the fundamental science questions shown below using intense data analyses:

1. What are the conditions in space (e.g., geomagnetic field and indices, ionospheric currents) that generate intense ground dB/dt variations as a function of IPS impact angles?

2. Do IPS impact angles control dB/dt variations and the associated ionospheric currents in different locations at the shock onset and during substorm-like events?

To address our science questions, we propose to use data of missions that compose the Heliophysics System Observatory (HSO), namely, ACE, Wind, THEMIS, RBSP, Geotail, ARTEMIS, and MMS, publicly provided by NASA's Space Physics Data Facility. In particular, we will perform multi-array investigations of ground dB/dt variations caused by shocks with different inclinations and: (i) construct an updated, validated shock list with shock impact angles; (ii) conduct case studies during inclined and frontal IPSs using multiple near-Earth satellites and multiple THEMIS ground magnetometers (GMAGs) and all sky image (ASI); and (iii) perform a statistical study and 2-D maps of dB/dt variations and ionospheric currents for inclined and frontal IPSs. 2-D maps of ionospheric currents will be produced by processing THEMIS/GMAG data with the spherical elementary current system technique. THEMIS/ASI data will be used to support the identification of substorm-like events. In the statistical analyses, all events will be grouped with respect to local times at the shock onset and maximum dB/dt associated with substorm-like events. To support these results, we will also examine how other shock parameters (e.g., speed, dynamic pressure) control the dB/dt generation by shocks.

This proposed effort is directly relevant to the NASA Heliophysics specific objectives advance our understanding of the Sun s activity, and the connections between solar variability and Earth and planetary space environments," and develop the knowledge and capability to detect and predict extreme conditions in space to protect life and society." In addition, this proposal is directly relevant to the HGIO program because it maximize[s] the scientific return from operating [HSO] missions by providing support for research that is beyond the scope of work of the mission science teams. Therefore, HSO provides unprecedented opportunity to address our proposed science questions which go beyond the science questions of the specific HSO missions.

Merav Opher/Boston University
Bridging the gap between modeled ENA maps and Observations

Global models of the heliosphere are critical tools used in the interpretation of heliospheric observations. Within the heliospheric community, there are several three-dimensional magnetohydrodynamic (MHD) heliospheric models which rely on different strategies and assumptions. Recently, Kornbleuth et al. (2021a) compared, the results of two different MHD models, the BU (Michael et al. 2021) and Moscow (Izmodenov & Alexashov 2015) models. Both models use identical inner and outer boundary conditions to compare how the inclusion of different numerical approaches and physical assumptions in the respective models contribute to the resultant heliospheric solution.

Despite differences in the heliotail of the two models, Kornbleuth et al. (2021b) demonstrated that the BU and Moscow models yield similar synthetic ENA maps of the heliosphere in post-processing. Both MHD models produce ENA maps that are both quantitatively and qualitatively similar at the IBEX-Hi (Funsten et al. 2009) energy bands (0.71-4.29 keV). This is because ENAs observed at the IBEX-Hi energy bands primarily originate within 200 AU of the termination shock in the heliotail, whereas differences between the MHD models manifest beyond 300 AU beyond the termination shock. In comparing with IBEX ENA data, the maps are qualitatively similar as well; however, the modeled maps are not quantitatively similar to the IBEX data. To provide agreement, the modeled maps must be scaled by a factor of 1.8. This quantitative difference is also seen in other ENA models that use the Maxwellian approximation for the modeled pick-up ion (PUI) populations, such as Zirnstein et al. (2017) which requires fluxes be scaled by a factor of 2.5. Both the Kornbleuth et al. (2020) and the Zirnstein et al. (2017) ENA models, in addition to the Baliukin et al. (2020) which uses a kinetic approach to PUI modeling, also do not provide good spectral agreement with observed ENA fluxes in the Voyager 1 direction.

We propose a 3-year study the physics necessary to address the differences that exist between ENA models and IBEX observations. With recent studies (Nakanotani et al. 2021; Giacaloni et al. 2021), we can more accurately predict the transmission of PUIs through the termination shock, which is a necessary ingredient for ENA recipes (Zirnstein et al. 2017; Kornbleuth et al. 2020; Baliukin et al. 2020). The difference between models and observations indicates that other processes in the heliosheath need to be invoked to reduce the discrepancy between modeled ENAs and observations. We will explore processes such as the acceleration of PUIs in the heliosheath (by reconnection or turbulence) and the thinning of the heliosheath (by thermal conduction) in order to understand which processes are critical for bringing agreement between modeled ENA maps and observations.

For this work, we will use the Solar-wind with Hydrogen Ion Exchange and Large-scale Dynamics (SHIELD) model, which couples the MHD solution for a single plasma fluid to a kinetic solution for neutral hydrogen atoms (Michael et al. 2021). Using the results of this MHD model, we will compare the model predictions to the IBEX ENA observations in directions that avoid regions where the IBEX ribbon (believed to be generated by ENAs originating from beyond the heliopause McComas et al. 2009) dominates the ENA flux, such as the Voyager 1 direction, the southern pole, and the downwind direction.

This proposal directly addresses two goals of the most recent Heliophysics Decadal Survey for Solar and Space Physics: to determine the interaction of the Sun with the Solar System and the interstellar medium and to discover and characterize fundamental processes that occur both within the heliosphere and throughout the Universe.

Andrei Runov/University of California Los Angeles
Structure of the Magnetotail Current Sheet at Lunar Distances

The goal of the proposed research is to understand physics of thin current sheets (TCS) in the mid-distant magnetotail. Thinning of the magnetotail current sheet followed by instability onset is the key element of the magnetotail dynamics. Observations revealed the formation of TCS with a thickness comparable to a proton thermal gyroradius at geocentric distances R from <10 to 30 Earth radii (RE). The growth rates for various instabilities, that lead to magnetic energy conversion into kinetic energy of particles, highly increase in such TCS.
Characteristics of the magnetotail current sheet in the near-Earth magnetotail (R <20 RE) and physics of TCS formation were comprehensively studied with multi-point observations. The mid-distant magnetotail (20<R<100), where the magnetic field is much weaker and more fluctuating than that in the near-Earth magnetotail, remains under-explored. We propose to use Turbulence and Electrodynamics of Moon s Interaction with the Sun (ARTEMIS) dual probe observations at lunar orbit (R~60 RE) to fill this gap.

To achieve the science goal we propose to characterize structure of current sheets observed by the ARTEMIS probes during quite time, when the local bulk plasma velocity does not exceed 100 km/s, and during tailward and earthward fast plasma flows (|V|>100 km/s). We propose to use flapping TCS crossings, which are indicated by a rapid decrease in the X GSM magnetic field component (Bx) absolute value from ~10 nT to 0 nT with subsequent change in the Bx sign, to apply the variance analysis and investigate i) distributions of normal (Bn) and intermediate (Bm) magnetic field components, ii) distributions of density, ion and electron temperatures and their anisotropy, and iii) ion and electron energy and velocity distributions as functions of the maximum variance magnetic field component (Bl).
The proposed methodology will allow us to address the following science questions:
SQ1: what is the magnetic structure of current sheets in mid-distant magnetotail and how does it change between quiet times and fast flow intervals?
SQ2: how are magnetic and plasma pressures balanced in the mid-distant magnetotail current sheet?

SQ3: how do particle distribution functions change with the distance from the magnetic equator in the mid-distant magnetotail current sheet during quiet times and during fast flow intervals?

The proposed research will advance our knowledge on the nature of intense current sheets in a weak and highly fluctuating magnetic environment, which is a fundamental space plasma physics problem. Results of the proposed investigations are of interest of a broad community including experts in physics of planetary magnetospheres, physics of solar and stellar winds, and astrophysics. Our proposal is directly relevant to NASA's Heliophysics' overarching goal and the specific objective: Explore and characterize the physical processes in the space environment from the Sun to the heliopause and throughout the universe .

Daniel Seaton/Southwest Research Institute
Probing the Origins of Outflow in the Middle Corona

Goals
We use remote sensing observations spanning multiple regimes to characterize the nature of emission in the middle corona (1.3 3 Rsun) and derive the conditions, processes, and magnetic connectivity that give rise to transient and steady outflows that become the solar wind. Specifically, we will determine:
1. The nature of emission from the middle corona across a broad range of wavelength regimes to derive the underlying physical conditions including temperature, density, composition, and other plasma properties.
2. The nature of magnetic connectivity through the middle corona, established by correlating observed features with their counterparts in data-driven global models.
3. The nature of different types of outflow that give rise to the solar wind and its embedded structure, as characterized by the above diagnostics, and the origins of such outflows from processes that occur in the low and middle corona.

Data
We initially target the period around the total eclipse of 2017 Aug 21 because of the extensive publicly available archive of coronal observations and models covering this event. The eclipse occurred well into the declining phase of the solar cycle and marked the onset of rising activity that culminated in major eruptions in September; observations of this period provide a broad sample of conditions ranging from quiet to very active. This eclipse generated a rich, extensive set of observations of the middle corona across the gamut of wavelengths and provides a unique opportunity to answer questions about the specific nature of emission from and structures within the corona that cannot be addressed with existing routine observations.

Our initial eclipse-focused study is generalized to multi-instrument, coordinated remote sensing campaigns between 2010 and early 2021. This includes SDO calibration maneuvers and several coordinated campaigns during Parker Solar Probe perihelia and Solar Orbiter commissioning activities. We leverage off-point campaigns from SDO/AIA, PROBA2/SWAP, and GOES/SUVI that provide EUV observations to >3

Rsun. Observations from Solar Orbiter provide a third (beyond Earth/STEREO) perspective to help characterize 3D structures.

Primary Data: (EUV) SDO AIA, STEREO EUVI, SolO EUI; (Visible) SDO HMI, LASCO C2/3, STEREO Cor1/2, SolO METIS; (X-ray) Hinode XRT
Secondary Data: (EUV) GOES SUVI, PROBA2 SWAP; (Visible) MLSO KCor, Citizen CATE Eclipse; (IR) NASA WB-57 MWIR Eclipse; (X-ray) GOES SXI

Methodology
We will determine coronal properties using a combination of image-processing and spectral analysis techniques, focused on identifying the complementary ways that each data set refines and constrains our picture of the plasma properties, morphology, and connectivity in the low to middle corona. We will also leverage existing global coronal models for the 2017 eclipse and new models covering the periods of our specific campaign events to connect these observations to the underlying physical state of the corona using a combination of novel forward modeling and 3D magnetic field analysis and mapping techniques.

Relevance
This proposal directly addresses NASA SMD s 2020 Science Plan goal to understand the Sun... . We also directly address Decadal goal 4 to discover and characterize fundamental processes... , specifically through subgoal SHP-2, Determine how the Sun s magnetism creates its hot, dynamic atmosphere.

Zoltan Sternovsky/University of Colorado
High-fidelity analysis of dust impact waveforms from STEREO A and B

This proposal will perform the new and significantly improved analysis of the Time Domain Sampler (TDS) data from the two STEREO A&B WAVES instruments in order to disentangle the populations of interplanetary and interstellar dust particles. The data from these two spacecraft provide unprecedented coverage of the interplanetary dust complex near 1 AU. While previous works have used the TDS data for calculating the fluxes of various dust populations, a recent advancement in the field warrants revisiting the data analysis.

The stacer booms of S/WAVES instruments are sensitive to plasma cloud generated by hypervelocity impacts of dust particles on the spacecraft body or the antennas. The TDS portion of the S/WAVES instrument registers voltage perturbation waveforms from all three antennas generated by direct charging and induced charging of the spacecraft and antenna elements from the dust impact plasma.

The new models of antenna signal generation are based on first principles, and account for the parameters of the impact plasma (effective plasma cloud temperatures and geometry of cloud expansion), the parameters of the ambient space environment, and the geometry of the spacecraft. The analysis of each waveform is achieved by fitting the data using the model, which provides the total impact charge and constraints on the location of impact. The impact charge is a measure of the dust particles mass, and the determining the impact location constrains the origin (and therefore velocity) of the dust particle. All prior studies used statistical guesses at the impact velocity and the origin of the particles, and used simplified models for the capacitances of the spacecraft elements and their interactions. We propose to apply the newest techniques and high-fidelity STEREO S/WAVES data to uniquely constrain the interplanetary and interstellar micron sized dust at 1 au observed over 15 years. The proposed research is directly relevant to Key Science Goals from the 2013 National Research Council Decadal Strategy for Solar and Space Physics report.

The dynamics of micron and submicron sized particles is governed by the Sun s gravity, radiation pressure, Poynting-Robertson drag, and the Lorentz force from the expanding solar wind plasma. The overarching science goal of the investigation is characterizing the various dust populations in the solar system near 1 AU. The specific objectives include: (1) Exploring the solar-cycle dependence of dust flux, in particular how total solar irradiance variations over a solar cycle impact the flux of Beta meteoroids through 1 AU. STEREO has been on-orbit since 2006 and provides data coverage for over 15 years, which is more than one full solar cycle. (2) Comparing the current zodiacal dust models to the observations of micron-sized dust particles. (3) Explaining the long-open question of why dust impacts on STEREO are preferentially detected by a single antenna, but a different antenna on spacecraft A and B.

As an additional benefit, the proposed refinement of dust impact waveform analysis will enhance the science return of other past, current and future missions, including Wind, Parker Solar Probe, Solar Orbiter, and a potential Interstellar Probe.

Daniel Vech/University of Colorado Boulder
Quantifying Energy Transfer Rates from Electromagnetic Fields to Protons and Electrons in Earth s Magnetosphere

Science Goals and Objectives:
Turbulent energy of the solar wind is continuously transferred into the terrestrial magnetosphere where it gets dissipated by various heating mechanisms such as Landau damping, stochastic heating and cyclotron damping, all of which lead to an increase in the thermal energy of protons and electrons. We propose to create a map of the magnetosphere based on the field-particle energy transfer rates, which will make it possible to compare the different regions of the magnetosphere, their underlying plasma conditions (plasma beta, magnetic turbulence amplitude, dominating wave mode on kinetic scales) and identify the ones, which are the most effective at dissipating the turbulent energy.

The proposed study became feasible due to the recent development of a field-particle correlation technique, which offers a powerful, new diagnostic tool to measure the energy transfer between electromagnetic fields and particles in space plasmas. This technique was successfully used to quantify energy transfer from electromagnetic fields to electrons in the magnetosheath of Earth using high cadence measurements from the

Magnetospheric Multiscale Mission (MMS). The overarching goal of the current proposal is to conduct a global statistical study of energy transfer rates to protons and electrons in the magnetosphere using the wave-particle correlation technique and answer the following science questions (SQ):

SQ1: What is the statistical distribution of the energy transfer rates to protons and electrons in the dayside, magnetotail and flank regions of the magnetosphere?

SQ2: How does the energy transfer rate depend on proton beta, magnetic turbulence amplitude, wave mode of the kinetic scale turbulence (kinetic Alfven wave vs. whistler wave) and geomagnetic activity?

Mission data to be used:
We will use the entire available burst mode database of MMS (2015-2021) including the Fast Plasma Instrument s (FPI) ion and electron velocity distribution functions (150 ms and 30 ms cadence, respectively) in conjunction with the electric field measurements (1/8192 s cadence). We will use the FPI and fluxgate magnetometer data to identify the background plasma parameters such as plasma beta, magnetic turbulence amplitude and wave mode of kinetic scale turbulence.

Methodology:
For our analysis we have identified 251, 40 and 176 hours of burst mode data in the dayside, magnetotail and flank regions, respectively. The average energy transfer rates to protons and electrons will be calculated for each 10 second interval. Three data products will be obtained for each particle species: average energy transfer rate 1) along and 2) perpendicular with respect to the background magnetic field and 3) the average net electromagnetic work done on a given particles species by the electric field. We will answer the SQs by studying the dependence of these three quantities on spatial locations and the underlying plasma conditions.

Relevance:
Energy transfer from electromagnetic fields to particles is a fundamental process in the plasma Universe and thus critical to NASA and its Decadal Survey Goal #4 Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe and also Survey Goal #2 Determine the dynamics and coupling of Earth s magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs. . This proposed work will enhance the science return of the MMS mission and, by characterizing energy transfer rates to protons and electrons in the magnetosphere, goes beyond the original mission goals. Successful completion of the proposed work will lead to clarification on where the particle thermalization takes place in the magnetosphere and how it depends on the underlying plasma parameters.

Juliana Vievering/Applied Physics Laboratory
Investigating Energy Release during Solar Eruptive Events

SCIENCE GOALS

The overarching science goal for this study is to understand the relationships among magnetic reconnection, flare energy release, and initiation/acceleration of coronal mass ejections (CMEs) for solar eruptive events with observed hard X-ray (HXR) emission. We will achieve this goal by investigating the following science questions:
(1) When and where do reconnection and flare energy release occur relative to CME acceleration for events in quiescent and active regions?
(2) How does intermittent reconnection and energy release relate to the magnetic configuration and impact the evolution of the CME-flare?

MISSION DATA

To study the CME kinematics, we will utilize data from the Solar Terrestrial Relations Observatory (STEREO) and the Solar and Heliospheric Observatory (SOHO). Data from the Solar Dynamics Observatory (SDO) will also be utilized to examine the early evolution of CMEs at a higher cadence and to measure the reconnection rate. HXRs, emitted from strongly heated flare plasma and from flare-accelerated electrons, will be used to study the location and evolution of flare energy release. We will use HXR data from the Reuven Ramaty High-Energy Solar Spectroscopic Imager (RHESSI), the Fermi Gamma-ray Burst Monitor (GBM), and, where possible, the Solar Orbiter Spectrometer Telescope for Imaging X-rays (STIX).

METHODOLOGY

We will extend beyond previous studies of CME-flares by examining fast-varying features, or bursts , in the HXR, reconnection rate, and CME acceleration profiles. These bursts represent episodes of energy release which can provide insight on reconnection and acceleration mechanisms during the eruptive event. We will consider the subset of CME-flares in [1] which have available RHESSI data, along with additional events occurring post-2013. Most notably, our list includes at least two events with rarely-studied HXR flares occurring outside of active regions; comparison of HXR CME-flares in active and quiescent regions will improve our understanding of how the magnetic configuration affects the evolution of eruptive events. This study will separately leverage RHESSI observations of partially occulted flares [2] that are associated with CMEs to measure nonthermal HXR coronal source emission, which provides the most direct signature of flare particle acceleration.

Standard RHESSI analysis tools will be used to produce light curves and images; the light curves will be detrended to identify fast-varying features. The CME kinematics will be measured by deriving height-time profiles from STEREO, SOHO, and SDO data, and time derivatives will be applied to compute the velocity and acceleration. Model-independent fitting procedures will be performed to capture fast variations in the CME acceleration profiles. The reconnection rate will be calculated using the method described in [1] with SDO data. In this method, the reconnection flux is computed by summing the photospheric magnetic fluxes in regions with brightening flare ribbons; a time derivative is then applied to determine the reconnection rate.

RELEVANCE

Our study is relevant to the Heliophysics overarching goal to understand the Sun and its interactions with the Earth and the Solar System, including space weather and to the combined objective to advance our understanding of the Sun s activity in ROSES Element B.1. The investigation of the relationships among flare energy release, the reconnection rate, and CME acceleration will offer insight into the initiation/evolution of solar eruptive events, which is crucial for solar activity forecasting. This work is also relevant to STEREO s objective 1 (the structure and magnetic morphology of CMEs...) and SDO s objective 4 (reveal the fundamental physics of solar atmospheric dynamics and eruptive events), as stated in the 2020 Senior Review.

REFERENCES

[1] Zhu et al. 2020, ApJ, 893, 141
[2] Effenberger et al. 2017, ApJ, 835, 124

Tongjiang Wang/The Catholic University of America

Probing Flare-Generated Slow-Mode Waves in Coronal Loops Detected by SDO/AIA

1. Scientific Objectives

Recent high-resolution and high-cadence EUV observations of MHD waves have allowed rapid development of a technique called Coronal Seismology (CS), which can be used to determine physical parameters of coronal structures that cannot be directly or easily measured. SDO/AIA has detected longitudinal intensity oscillations in hot flaring loops exhibiting similar physical properties as those of standing slow magnetoacoustic waves observed with the SOHO/SUMER spectrometer in Doppler velocity measurements. Evidence of significant suppression of thermal conduction in a heated ($T > 9$ MK) loop was found previously using the CS analysis. This result suggests a new, promising possibility that anomalously enhanced compressive viscosity may be the dominant wave-damping mechanism. Understanding the anomalous transport processes may shed light on the physical properties of flaring plasma, wave excitation mechanism, and long-standing puzzles such as long-duration EUV/X-ray flares. In this project, we propose to pursue the following scientific objectives:

a) Explore the wave excitation (agent and mechanism), measure the formation time of a standing mode, and characterize the heating sources and the physical properties of longitudinal oscillation events.

b) Derive the transport coefficients from measured wave and plasma properties, and determine whether anomalous transport processes, such as thermal conduction suppression and viscosity enhancement, are common in flaring loops.

c) Examine whether the formation time of a standing slow-mode wave depends on the magnitude of compressive viscosity in the flaring plasma, and whether the slower-than-expected cooling of the flare decay phase is associated with the suppression of thermal conduction.

2. Data to Be Used

This project will utilize existing publicly available data mainly from SDO/AIA and HMI, with supporting data from several other missions including RHESSI, Fermi/GBM, Hinode/XRT, and IRIS. We will assemble a catalogue of about 30 flaring loop oscillation events for our analysis.

3. Methodology

We will identify wave modes (standing or reflected propagating waves) from time-distance plots and characterize the wave excitation agent such as heating sources and the associated magnetic configuration. We will obtain time profiles of the loop temperature and density from differential emission measure (DEM) analysis, and measure amplitudes of temperature and density oscillations and their phase shifts. We will determine the effective transport coefficients using a field-aligned hydrodynamic (HD) loop model by best fitting to the observed oscillations. We will evaluate the validity of the 1D HD CS method and examine the effects of modified transport coefficients on the wave excitation, MHD mode couplings, and thermodynamic evolution of heated plasma in the flaring loop based on 3D MHD simulations using existing numerical codes.

4. Relevance

The proposed investigation is to determine the presently poorly known values of the transport coefficients in flare-heated coronal loops and based on these measurements to advance our understanding of fundamental processes such as excitation and dissipation mechanisms of MHD waves and the energy transport in flares. This investigation is thus in line with the Decadal Survey goals: "Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe". Our primary data source is SDO/AIA. The proposed analyses are in line with the AIA's two core research themes "energy input, storage, and release" and "coronal seismology".

Xiaojia Zhang/University of California Los Angeles

Energetic Electron Scattering by Kinetic Alfven Waves in Earth's Radiation Belts

The flux intensity of energetic electrons in Earth's outer radiation belt is due to a delicate imbalance between transport, acceleration, and losses. Wave-particle interactions contribute critically to all three of these competing processes. Chief amongst them are ULF wave-related transport, whistler-mode chorus associated acceleration, and EMIC or hiss wave related losses. Although a combination of these interactions can explain the evolution of energetic electron fluxes over long timescales (tens of hours to days), rapid electron flux variations cannot always be explained by them. One important discrepancy is the rapid dropout of 0.1-1 MeV electrons. These energies are too low to be scattered by resonant interactions with EMIC waves, whereas the dropout timescale is too short to be explained by the scattering rates from whistler-mode hiss waves. One possible candidate is the scattering by Kinetic Alfven waves (KAW). KAW can potentially resonate with these high-energy electrons and scatter them into the loss cone, but contribution of this wave mode to radiation belt dynamics has not been thoroughly studied. Therefore, the primary goal of this project is to quantify the KAW contribution to energetic electron scattering in the radiation belts.

Theories have shown that KAWs can scatter 0.1-1 MeV electrons due to drift-bounce resonance near the equator. In fact, observations of these waves are common as broadband electric and magnetic field fluctuations below ~100Hz. Although KAWs are rather widespread (and most powerful in the aftermath of plasma sheet injections or in the presence of plasma density gradients, e.g., at the plasmapause), their contribution to energetic electron losses has not been quantified yet. Thus, our first objective is to explore direct evidence of KAW resulted electron precipitation, using combined near-equatorial and low-altitude observations. Specifically, we will analyze conjugate observations of KAWs by near-equatorial NASA missions (THEMIS, MMS, and Van Allen Probes) and precipitating energetic electrons by ELFIN (low-altitude twin CubeSat mission).

Evaluation of pitch-angle diffusion rates by KAWs requires a set of assumptions, which need to be verified with direct spacecraft observations before being incorporated into radiation belt models. The second objective is thus to verify the KAW diffusion rates by comparing the expected and observed precipitating electron fluxes in multiple conjunction events. To do this, we will estimate precipitating electron fluxes from near-equatorial wave and electron measurements (mainly from recent THEMIS, MMS, and Van Allen Probes) and compare these fluxes with direct observations from ELFIN. The third objective is to statistically investigate the KAW contribution to energetic electron precipitation. Specifically, we will evaluate precipitating electron fluxes based on statistics of KAWs from near-equatorial spacecraft (THEMIS, MMS, and Van Allen Probes) and compare these fluxes with the statistical pattern of precipitating electron fluxes from ELFIN.

This project will improve our understanding on mechanisms of energetic electron losses in the inner magnetosphere (including radiation belts). We focus on electron resonant interaction with Kinetic Alfven waves, which is ubiquitous in planetary magnetospheres and solar wind. Therefore, our proposal is relevant to NASA's Heliophysics' overarching goal and the specific objective to: Explore and characterize the physical processes in the space environment from the Sun to the heliopause and throughout the universe .

Living With A Star Program (LWS21)
Abstracts of Selected Proposals
(NNH21ZDA001N-LWS)

Below are the abstracts of proposals selected for funding for the Living With A Star Program (LWS21). Principal Investigator (PI) name, institution, and proposal title are also included. Sixty-six (66) proposals were received in response to this opportunity. On April 27, 2022, twenty (20) proposals were selected for funding.

Cynthia Cattell/University Of Minnesota
Investigating the radial evolution of the interactions between solar wind plasma, macroscopic structures, and intermediate frequency waves

One of the key problems in developing accurate models for predicting space weather is understanding the co-evolution of waves and particles with solar radial distance. The coupled processes modify the temperature, energy and momentum of solar wind plasma, which are critical parameters for determining the interaction of the solar wind with the Earth's magnetosphere, and, ultimately how changes in the Sun impact life and technology. Our overall science goal is to determine nature of the interactions between intermediate frequency waves and large-scale solar wind structures and electrons and ions as they stream away from the Sun. We define intermediate frequency waves as approximately the range from the lower hybrid frequency to the ion plasma and electron cyclotron frequencies. We will concentrate on the evolution between ~15 solar radii (reached by Parker Solar Probe during encounter 8) and ~1 AU.

To address our science goal, we will focus on these specific questions:
1. What is the interdependence between intermediate frequency waves and large-scale structures including interplanetary shocks and stream interaction regions?

2. How do the occurrence, properties and dominant instability mechanisms of intermediate frequency waves depend on distance from the Sun?

3. How do the changes in dominant wave modes impact the evolution of electrons and ions?

4. Near 1 AU, how do these waves depend on solar cycle?

Technical approach: We will utilize in-situ plasma and waves data from spacecraft at varying distances from the Sun to examine wave properties and occurrence rates, and their relationship to electron and ion properties. We will focus on data from Parker Solar Probe, STEREO and Wind. As necessary to increase statistical significance or to examine regions farther from the Sun, we will use data from Solar Orbiter, Cluster, ARTEMIS, Cassini, and Juno. Waveform capture data provide the most detailed information on wave modes and properties, while on-board spectra and bandpass filter data yield the continuous (or longer duration) observations needed to accurately assess occurrence rates and radial dependence. STEREO and Wind provide data over multiple solar cycles to assess changes in the waves and particles with solar cycle at ~1 AU. We will utilize cold and warm plasma dispersion relation solvers, and fully kinetic simulations (FKS) simulations to determine instability mechanisms. Both particle tracing codes and (FKS) simulations will be used to assess the interactions of the waves with particles. Errors in data sets and data analysis and in theoretical techniques will be addressed.

Relevance to goals of LWS and of FST 3: Our science objective and questions are directly relevant to FST 3, specifically to the goals to understand (1) the physical processes driving the formation and propagation of solar-wind structures throughout the heliosphere and their variability with the solar cycle and (2) how the solar magnetic field and coronal structure determine the plasma and magnetic-field conditions in the inner heliosphere throughout the solar cycle." As described above we will establish how solar wind particles interact with intermediate frequency waves at different distances from the Sun , and, in addition, the solar cycle dependence around 1 AU. Our contribution to the Science Team effort will be providing a detailed understanding of the physics of intermediate frequency waves, their role in the radial evolution of solar wind plasma, and interactions with macroscopic solar wind structures. The insights we develop will be important for other teams , for example those who are examining MHD turbulence, the connectivity of solar wind structures to the solar corona, and evolution of the solar wind to the outer parts of the heliosphere. The new understanding that will be obtained through our research is needed to develop accurate predictive models for space weather, thus safeguarding life and technologies.

Rohit Chhiber/University Of Delaware

The Influence of Structure and Turbulence on Coronal and Heliospheric Dynamics - Improved Magnetohydrodynamic Modeling with Data-driven Subgrid-scale Effects

The solar wind is a complex and dynamic system that involves interactions across multiple physical and temporal scales. Global magnetohydrodynamic (MHD) simulations coupled to subgrid-scale turbulence models incorporate such cross-scale couplings, and are a valuable tool for providing context for in situ observations and for studying a variety of problems that involve the interplay between large-scale structure and turbulence. A crucial input to these models is provided by solar photospheric magnetograms. However, models, which typically have relatively coarse resolution, are unable to utilize the full information available in high-resolution (hi-res) magnetograms. Here we propose a novel approach for extracting high-wavenumber" information from these magnetograms and incorporating these data in our simulations. This will expand the physics contained within the model and help us better understand the magnetic field's influence on coronal and heliospheric structure and dynamics.

In particular, we propose the following focused research tasks -
1) Use a novel approach to estimate magnetic turbulence levels at the photosphere, by applying filtering methods on hi-res magnetograms to compute small-scale fluctuations.
2) Use these turbulence levels as data-driven, spatially-varying input for our model, which will produce distributions of large-scale fields and turbulence parameters through the inner heliosphere, thus enabling investigation of effects of photospheric turbulent variations on acceleration, heating, and dynamics of the inner-heliospheric plasma. Simulation results will be compared with in situ observations, to test model performance and provide 3D context for observations.
3) Apply the model to study magnetic field-line random walk (FLRW), and its effect on magnetic connectivity between solar sources and heliospheric observation points. Statistical approaches will be used to study FLRW, and evaluate related effects on field-line path-lengths and meandering in longitude/latitude. Implications for energetic particle transport will be considered.
4) Apply the model to study azimuthal flows in the young solar wind, including investigation of the effect of turbulence on angular momentum loss of the Sun, and on the morphology of the Alfven surface. This problem is of particular contemporary relevance in light of recent observations [1] of unexpectedly strong azimuthal flows by Parker Solar Probe (PSP).

By linking a novel analysis of photospheric turbulence to the dynamics of the extended solar atmosphere, and by applying our model to the focused problems listed above, we aim to arrive at an improved understanding of the magnetic field's influence on the heliosphere, as well as the radial evolution of magnetic connectivity.

Methodology: We will use (and improve) well-tested 3D MHD simulations of coronal and solar wind that include turbulence modeling [2]. Effects of long-term solar variability will be incorporated by varying source dipole tilts and by using magnetograms (e.g., ADAPT, HMI) from different epochs. In situ observations from several missions, including PSP and Solar Orbiter, will be compared with the model. Standard diffusion-theory approaches will be used to study FLRW.

Relevance to FST: The proposed research will support FST#4 by achieving an improved understanding of the structure, evolution, and influence of the magnetic field from the solar photosphere to the inner heliosphere, focusing in particular on the interplay between turbulence and large-scale dynamics. 3D distributions of large-scale flow and turbulence parameters from our model can potentially be used to provide global context for more local investigations by other teams.

[1] Kasper et al., Nature, 576 (2019); [2] Usmanov et al., ApJ, 865:25 (2018)

Xiangning Chu/University Of Colorado, Boulder
Understanding plasmaspheric refilling: an investigation using machine learning models and physics-based simulation

Science description

The plasmasphere consists of cold plasma (~1 eV) at mid- to low- L-shells surrounding the Earth. The plasmaspheric density and composition strongly influence energetic particle scattering and acceleration, wave propagation, wave-particle interactions. Therefore, it is essential to understand the plasmaspheric dynamics, i.e., the plasmaspheric erosion and refilling under various geomagnetic conditions. However, previous studies are limited by the lack of in-situ satellite measurements of the cold plasma at ideal locations and at any time. For example, satellite measurements following the motion of flux tubes are essential but missing how flux tubes are refilled. To resolve this issue, machine-learning (ML-) based models of the cold plasma, including total plasma density and different ion species, will be developed to provide global and time-dependent reconstructions of the cold plasma and ion species at any location (e.g., following any flux tube, or on the equatorial plane), and at any time (e.g., during the storm recovery phase). In addition, a physics-based model of the ionosphere, plasmasphere, and electrodynamics (IPE) will be compared to the ML-modeled semi-observations to aid in interpretation and study the mechanisms governing plasmaspheric refilling.

The main goal is to understand the typical characteristics and governing mechanisms of the cold electrons and ion species during plasmaspheric refilling using machine learning models and physics-based simulations.

The main objective is to answer the overarching science question: how are the cold electrons and various ion species refilled under different geomagnetic activity?

Specific science questions that will be addressed are:

1. How is the total electron density of the plasmasphere refilled?
2. How are the different ion species (H+, He+, and O+/N+) refilled?
3. What are the physical mechanisms controlling the refilling for each particle population?

Methodology

The proposed project will use in-situ data from the HOPE and EMFISIS instruments onboard NASA's Van Allen Probes; solar wind conditions and geomagnetic indices as driving conditions; machine-learning models of total plasma density and ion species, and physics-based IPE model. Specifically, to address:

1.Q1 and Q2: the refilling rates of the total plasma and ion species will be evaluated using the ML-modeled densities along flux tubes at different locations and different phases of geomagnetic activity.

2.Q3: the contribution of physical mechanisms will be evaluated using the physics-based IPE model, whose results will be cross-validated with and matched ML-modeled semi-observations.

The uncertainty of the ML-based model will be evaluated as a function of locations. The uncertainty of the IPE model will be quantified using sensitivity analysis.

Relevance

Our study focuses on the cold plasmasphere and its drainage plume, which is the targeted plasma population of the FST target. Our project contributes to FST #3, objective 1 (refilling of the plasmasphere, &and factors controlling these sources), objective 2 (the evolution of the plasmasphere), and objective 4 (determination of the properties and controlling factors of the low-energy electron and ion populations) in section 3.2. Our study uses machine learning models and physics-based simulations, which fits the types of investigation in section 3.3. The ML-based models will contribute semi-observations with uncertainties to the FST team, which serves as a comparison basis to validate first-principle models. The IPE model will provide the evolution of cold electrons and ions species in the plasmasphere under different geomagnetic activities. The metrics of success will be the model performance of the empirical model and IPE model. The milestones include the development of the ML-based model, model application to event studies, and comparison to the IPE model to understand the physical mechanisms of plasmaspheric refilling.

Shantanab Debchoudhury/Embry-Riddle Aeronautical University, Inc.

Ionospheric responses to thunderstorm-generated acoustic and gravity waves over the continental US

Intense convective systems like thunderstorms are known to generate acoustic and gravity waves (AGWs) that may reach ionospheric heights, induce complex dynamics, electromagnetic effects and seed self-evolving plasma instabilities and ionospheric irregularities including traveling ionospheric disturbances (TIDs). AGW detection and induced effects are routinely reported using ground- and space-based instrumentation. However, the characteristics of the AGW sources and the neutral and ionized background states along the path of AGW propagation, that facilitate the generation of detectable disturbances in the ionosphere, need to be understood and quantified. The continental US experiences significant thunderstorm activity in the summer months, with the mid-west identified as a global hotspot for convectively generated AGWs. This, along with the high density of suitable instrumentation, make it the perfect location for studying these phenomena. Our proposal attempts to study the dynamics, conditions and the extent of the impact of thunderstorm-generated AGWs on the mid-latitude ionosphere over the continental US. In particular, we propose to address the following science questions (SQs):

1. What are the solar, geomagnetic, and atmospheric and ionospheric conditions that lead to detectable TIDs from thunderstorm-generated AGWs?
2. What are the amplitudes and temporal and spatial characteristics of TIDs occurring in the presence of thunderstorm activity?
3. What are the momentum and energy depositions of thunderstorm-generated AGWs into the mid-latitude ionosphere and the related electrodynamic effects?

To address SQs 1 and 2, we propose to use multi-layer observations for events associated with thunderstorm activity. Lower and middle atmospheric observations include NEXRAD radar reflectivity and rainfall rate maps to infer thunderstorm activity,

brightness temperature perturbations showing gravity waves in the stratosphere from the Atmospheric Infrared Sounder (AIRS) on NASA's Aqua satellite, and data from the Cloud Imaging and Particle Size (CIPS) instrument on the Aeronomy of Ice in the Mesosphere (AIM) satellite. The impacts on the ionosphere will be studied using multi-constellation GNSS total electron content (TEC) observations and ground scatter from the SuperDARN radars that show evidence of irregularities like MSTIDs, as well as airglow imagers and available ionospheric satellite data. We will study the co-occurrences of ionospheric irregularities over simultaneous occurrences of thunderstorms, AGWs and TIDs, and create a database of events from 2010-2020, spanning the majority of Solar Cycle 24.
To address SQ3, we will perform a set of parametric and case-study modeling investigations with the use of our state-of-the-art full-physics-based three-dimensional coupled atmospheric and ionospheric models MAGIC and GEMINI, spanning the atmospheric and ionospheric dynamics from the ground to exobase heights. The simulations will include highly realistic specifications of thunderstorm-generated AGWs based on NEXRAD observations, and background atmospheric and ionospheric states based on empirical and climatological models and observations.
The science objectives of this proposal directly address the LWS 2021 solicitation and in particular Focused Science Topic (FST#1), which seeks to understand the impact of terrestrial weather on the Ionosphere-Thermosphere system. The proposed effort includes observational- and modeling- based study to address the variability in the ionosphere thermosphere mesosphere (ITM) system from upward propagating AGWs over convection sources. The science goals are directly applicable to the LWS Strategic Science Areas SSA-VI and SSA-VII and also aligns with the NASA Heliophysics Decadal Survey science goal 2, Determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs".

Cooper Downs/Predictive Science Inc.
Linking Surface Magnetic Fields to the Structure and Dynamics of the Solar Corona

We propose a focused, four-year study to understand the links between high resolution photospheric magnetic fields and the structure and dynamics of the solar corona. Our approach will be twofold: First pushing the boundaries of what is possible with data driven coronal modeling to understand how surface fields regulate magnetic complexity, heating, and plasma dynamics in the solar corona. Second, applying what we learn towards the practical interests and goals of the LWS program. In particular, we will focus on the following key questions:

1. How does the modeled coronal connectivity, heating, and plasma structuring change with the spatial resolution of the quiet Sun network and inter-network fields measured at the surface?

2. How does the evolution of these fields at the surface modulate coronal dynamics and connectivity across a range of spatiotemporal scales?

3. How do choices made in creating photospheric boundary conditions (observables, inversions, averaging) subtly influence our coronal solutions?

4. How can we better encapsulate subgrid" structure and dynamics in our simpler models of the global corona and inner heliosphere?

To address these questions, we will conduct focused experiments using a state-of-the-art MHD model of the global solar corona, driven by high-resolution measurements of the surface magnetic field. Our experiments, divided into a series of study arcs, will use extremely high-resolution patches within a global domain to understand out how and why small-scale structure and dynamics at the surface may influence not only the properties of the low solar corona, but the solar wind and inner heliosphere as well. Leveraging high-quality spectropolarimetric measurements of surface field distributions from Hinode/SOT and simultaneous measurements from SDO/HMI, we will also study how choices of observables, inversion methods, and spatiotemporal processing methods may subtly influence coronal model solutions. To complement our analysis of the physical processes occurring in the simulations and their differences from run to run, we will use magnetic field connectivity mappings and topological indicators to inform and interpret our results. We will also place our results directly into observational contexts by forward modeling extreme ultraviolet and white-light polarized brightness observables from SDO, STEREO, SOHO, and MLSO.

Our project is designed to address much of the stated scope of LWS FST 4: Towards a Quantitative Description of the Magnetic Origins of the Corona and Inner Heliosphere". We specifically target two of the three stated goals of the FST: aiming to better understand how magnetic connectivity evolves from the photosphere to the inner heliosphere and how the magnetic field drives coronal and heliospheric structure and dynamics. Our investigation is quite relevant to the stated context of the FST, being not only a physics-based study that connects surface-field distributions to the heliosphere, but one with a specific focus on how the properties of photospheric magnetograms, both vector and line-of-sight, might influence coronal and heliospheric models. This aspect, along with our aim to explore evolution and structure at higher spatiotemporal scales than previously possible---which may play an important but subtle subgrid role in our coronal and heliospheric models---has not only scientific relevance, but implications for practical modeling and key aspects of data/model uncertainty. Lastly, our project fits naturally within the larger Focused Science Team effort, as we will be well positioned to incorporate other potential surface field data products and methods in our modeling study, to forward model other remote-sensing or in situ measurements that may be of interest, and/or to provide helpful insights, data, or modeling products for related studies on these topics.

Philip Erickson/Massachusetts Institute of Technology
Midlatitude topside ionospheric variations associated with plasmaspheric erosion and refilling

The plasmasphere and ionosphere are a tightly coupled dynamic system. Plasmaspheric flows can produce nighttime midlatitude ionospheric anomalies. At storm main phase, plasmaspheric erosion temporarily depletes large regions due to enhanced sunward flow expanding equatorward, with subsequent refilling during storm recovery phase. Ionospheric storm-enhanced density, with a magnetic dual in plasmaspheric plumes, appears to be uplifted and sometimes is situated within ion upflow regions. During the recovery phase, plasmaspheric refilling takes place principally via diffusion, established by balance between gravity and plasma pressure gradients. Ionospheric storm recovery creates a negative storm phase when reduced mid / low latitude thermospheric O/N2 changes occur. These ionosphere-plasmasphere mass exchange processes have significant geospace impact including alteration of ion trajectories in the inner magnetosphere in the presence of cold plasma, extending the reach of these influences into magnetospheric configuration. Frequency of storm occurrence keeps this process inherently dynamic. Throughout, the topside ionosphere is a key and dynamic region.
We will focus on the following science questions: (1) What are characteristic topside ionospheric variations associated with plasmaspheric erosion and refilling during geomagnetic storm main and recovery phases? (2) During plasmaspheric erosion and refilling, what is the influence of topside ionospheric dynamics on plasmaspheric and inner magnetospheric cold plasma populations? (3) What are controlling factors and physical processes in topside ionospheric recovery?
To address these questions, we propose 8 research tasks to analyze cold plasma density in the topside and other ionospheric altitudes, plasma temperatures, and thermospheric column O/N2 to gauge dynamic and chemical processes which are important for topside ionospheric recovery. We will study cold plasma state parameters in the plasmasphere and inner magnetosphere, and establish linkage with topside ionospheric sources during the short-term storm main phase and long-duration recovery phase. We will also provide ionospheric upflow estimates in the topside, and gauge ionospheric storm recovery/plasmaspheric refilling.
Primary 2012-2019 datasets (with maximum data overlap) include DMSP and Swarm density and velocity, GNSS topside TEC from LEO satellites GRACE, TSX, Swarm-A, Swarm-B, and MetOp-A, and GUVI column O/N2. This will be augmented by Millstone Hill incoherent scatter radar observations as well as GNSS TEC and ionosonde observations. We will also use Van Allen Probes A and B measurements of inner magnetospheric cold plasma density, electric field, and cold ion composition and THEMIS A, D, and E inner magnetospheric measurements of cold plasma density.
Our work will study topside ionosphere source plasma and in-situ cold plasma dynamics in the plasmasphere and inner magnetosphere, addressing FST SSA-V (Dynamics of the Global Ionosphere and Plasmasphere) and SSA-IV (Variability of the Geomagnetic Environment) and focusing on FST #2: the cold plasmasphere, drainage plume and refilling. Our LWS FST team contribution will include data and analysis of topside ionospheric recovery characteristics as a comparison basis for team validation of first-principle models with an ionospheric component. Joint analysis of topside ionosphere and

inner magnetosphere cold plasma configuration and dynamics will provide coincident information for these same models on plasma sources and evolution within the coupled ionosphere and plasmasphere (and inner magnetosphere).

Mei-Ching Fok/NASA Goddard Space Flight Center
Understanding the Sources, Recirculation, and Impacts of Cold Plasma with Self-Consistent Modeling

Science Objectives:
SO1. Understand the factors controlling the refilling rate of the plasmasphere.
SO2. Follow the pathways of cold plasma from its source to the drainage plume, to the magnetotail and back to the plasmasphere region.
SO3. Determine the impacts of cold plasma on reconnection rates and mass loading in the magnetospheric system.

The plasmasphere is the cold (< 10 eV) plasma population that resides in the inner magnetosphere. It is well established that the plasmasphere provides the environment for the generation and excitation of various plasma wave modes. These plasma waves, in turn, serve as agents or avenues for cross-energy coupling between the ring current and radiation belt particles. Nevertheless, relatively little attention is given to quantify the sources of the plasmasphere particles. What are the controlling factors of the refilling rate? On the other hand, the fate of the plasmasphere particles that encounter the dayside magnetopause is also poorly understood. Are they just lost in the solar wind? What fraction of them re-enter the magnetosphere? Moreover, what fraction of these re-entered particles are transported back to the inner magnetosphere? Furthermore, what are the impacts of the cold plasma on the global magnetospheric system? How much does the drainage plume reduce the dayside reconnection rate and thus the efficiency of energy coupling between the solar wind and the magnetosphere? How much does the mass loading effect from the plasmasphere influence the dynamics of the global magnetosphere?

Methodology:
A combination of global simulation and data analysis will be employed to address our science objectives. In this investigation, a multifluid MHD code (Block-Adaptive-Tree Solar-wind Roe-type Upwind Scheme [BATS-R-US]) combined with a comprehensive inner magnetosphere-ionosphere (CIMI) model will be our main modeling tool. A plasmasphere model has been embedded in the CIMI model. The plasmasphere model calculates spatiotemporal plasmaspheric density distribution considering corotation, convection, daytime refilling, and nightside diffusion. In this investigation, the refilling rate will be estimated by the SAMI3 (Sami3 is Also a Model of the Ionosphere) model. Critical to this investigation is the recent inclusion of a separate plasmasphere fluid in the multifluid BATS-R-US code. That fluid is filled from the CIMI code based on its embedded plasmasphere model. Outside the CIMI domain, the plasmasphere fluid continues to evolve based on the MHD calculation. We thus are able to follow the cold

plasma from its source to the plasmasphere region and to the global magnetosphere. Our simulation results will be compared with observations. The main data sets that will be analyzed are the particle and field data from the NASA Van Allen Probes mission. The plasmasphere density can be inferred either from the upper hybrid wave frequency or from the spacecraft potential.

Relevance:
The proposed study is relevant to Focused Science Topic #2: Pathways of Cold Plasma through the Magnetosphere. The investigation directly addresses the Focused Science goals of understanding the sources, evolution, recirculation and impacts of the cold plasma in the magnetosphere. This investigation will improve our predictive capability of the temporal and spatial characteristics of the plasmasphere. Our investigation has significant space weather relevance since the plasmasphere region constitutes a safe haven for spacecraft surface charging. We will perform CIMI-BATS-R-US simulations for events selected by the Focused Science Team. We will also provide simulation support to the team as needed.

Konstantin Gamayunov/Florida Institute Of Technology
The source of warm plasma cloak due to ion heating by EMIC waves

Goal and Objectives: Our overarching goal is to systematically investigate the source of warm plasma cloak due to heating of low-energy ions by electromagnetic ion cyclotron (EMIC) waves. To achieve this goal the following two objectives will be fulfilled. The 1st objective is to investigate in detail the individual cases of O+ and He+ heating and geomagnetic trapping due to dissipation of the He- and H-band EMIC wave energy, respectively. The 2nd objective is to produce the global geomagnetically dependent maps of the O+ and He+ heating and trapping parameters due to interaction with EMIC waves. On the global (MLT, L)-scale and during different geomagnetic conditions, we will quantify the energy and pitch angle ranges of ions interacting with EMIC waves, their densities, the energies per ion gained during EMIC wave events and the resulting increase of pitch angles, the observed distribution functions of those ions, and the concurrent EMIC wave and background plasma parameters including its ion fractions.

Methodology: There are two dominant bands of EMIC waves in the Earth's inner magnetosphere, where the He-band is the dominant one, which is followed by the H-band. The former band effectively heats low-energy O+, and the latter one heats He+. We will analyze all the He- and H-band EMIC wave events observed by the two Van Allen Probes from the beginning through the end of mission. For each event, all the needed wave and plasma parameters, DC magnetic field, and ion distribution functions will be taken from Van Allen Probes during the event. The observational data will be used to separately calculate the damping rates for He- and H-bands due to interactions with O+ and He+, respectively. Our damping rate code will allow us to identify 1) the O+ and He+ energy and pitch angle ranges that contribute most in the damping rates, and so to integrate the observed ion distributions to get number densities of those ions. Then, using the observed frequency spectra of EMIC waves and calculated damping rates, we will calculate 2) the wave energy dissipated during each wave event that gives us the energy per ion absorbed by the heated in the perpendicular to magnetic field direction O+ and He+, and 3) the resulting increase of the O+ and He+ pitch angles that shows us whether an additional geomagnetic trapping of the upflowing ionospheric ions is produced by waves. Finally, using the results from all the individual cases analyzed, the global geomagnetically dependent maps of the wave induced O+ and He+ heating and trapping parameters will be produced.

Van Allen Probes Data to be Used: 1) EMFISIS to get DC magnetic field, the high-resolution magnetic field for waves, and electron number density estimated from the upper hybrid frequency, 2) EFW for electron number density estimated from spacecraft potential, and 3) HOPE to get distribution functions of O+, H+, and He+ and also to estimate the ion fractions.

Relevance and Contributions to the FST: This effort will provide a better understanding of the warm plasma cloak sources by investigating its specific source due to heating of low-energy ions by EMIC waves, and so it is relevant to the FST #2: Pathways of Cold Plasma Through the Magnetosphere. The potential contributions of proposed study to this FST's effort are 1) a quantitative understanding of the source of warm plasma cloak due to ion heating by EMIC waves and 2) the global (MLT, L) and geomagnetically dependent maps of the O+ and He+ heating and trapping parameters due to interaction with EMIC waves that include the energy and pitch angle ranges of ions interacting with EMIC waves, their densities, the energies per ion gained during EMIC wave events and the resulting increase of pitch angles, the observed distribution functions of those suprathermal ions, a likelihood of an additional wave induced geomagnetic trapping of ions, and the concurrent EMIC wave and background plasma parameters including its ion fractions.

Larisa Goncharenko/Massachusetts Institute of Technology
Imprint of stratospheric QBO on the thermosphere and ionosphere

Science goals and objectives
During the past decade or so, it has been established that the troposphere-stratosphere region drives ionosphere-thermosphere-mesosphere (ITM) variability through generation of a spectrum of vertically propagating waves, including planetary waves, tides, and gravity waves. It was also revealed that the stratospheric Quasi-Biennial Oscillation (QBO) is one of the significant sources of variability in the mesosphere and lower thermosphere (MLT). However, studies of the QBO signature in the ITM are challenging due to the complex nature of the sun-atmosphere ionosphere system. In particular, earlier studies of links between the stratospheric QBO and the ionosphere remain inconclusive due to similar oscillations in solar flux.
This project strives to identify and quantify the imprint of stratospheric QBO on the ITM. It is well known that changes in the middle atmosphere wind are associated with tidal

amplification and larger ionospheric variability during transient events such as sudden stratospheric warming. We hypothesize that stratospheric wind changes associated with the QBO produce tidal variability on QBO time scales and, consequently, are imprinted on ionospheric electron density. Moreover, the QBO-related variation in non-migrating diurnal tides in the MLT can modulate the equatorial ionospheric anomaly wave-4 longitudinal structure. Confirmation of this hypothesis will provide a basis for improved physical understanding of additional terrestrial sources of ionospheric variability, and it will have implications for the prediction of ionospheric conditions on short-term, sub-seasonal and interannual time scales.

Methodology

We will use a combination of space-based and ground-based data to identify anomalies in the ITM that are associated with the westerly and easterly stratospheric QBO phases, and study impact of different QBO phases on the ITM variability. TIMED SABER and TIDI data will be used to determine impact of QBO on tidal amplitudes. Observations of O/N2 from TIMED GUVI will be used to isolate QBO signatures in the ITM. We will develop localized empirical models of total electron content (TEC) and peak electron density at several latitude/longitude locations to form a broad grid, using 20+ years of data of GNSS TEC observations and multiple ionosondes. These models will be used to separate TEC/NmF2 variations attributed to solar flux, season, latitude, longitude, and local time from variability induced by the stratospheric QBO. We will use NASA MERRA2 data products to examine the importance of several tropospheric and stratospheric parameters as independent drivers for empirical ionospheric models for multiple distinct low-latitude locations. In addition to standard linear regression models, we will use machine learning tools and investigate the use of nonparametric regression (e.g. Gaussian processes and neural networks) to formulate our empirical models and select the most appropriate set of terrestrial drivers for the final models. Simulations with WACCM-X constrained with MERRA-2 will be employed to interpret variability of tidal dynamics in the MLT region for different phases of QBO and their subsequent impact on the thermosphere and ionosphere.

Relevance and Proposed Contributions to the FST Effort

This project is directly relevant to the scientific objectives of the FST, as it will identify and quantify the relative role of stratospheric QBO in the ITM variability on sub-seasonal and longer time scales. Our team will contribute unique capabilities to the FST effort: (1) Observations-based characterization of QBO in ITM parameters at low and middle latitudes; (2) Model-based understanding of driving mechanisms that cause QBO in ITM; (3) Numerous data sets, numerical simulations, and empirical models developed during the project will be provided to the FST team to enhance other studies.

Jia Huang/University Of Michigan, Ann Arbor
The Alfvénic Slow Solar Wind Over Multiple Solar Cycles

SCIENCE GOALS AND OBJECTIVES: The slow solar wind is of great value for further investigations in regard to both science and application concerns. In general, the slow solar wind shows low Alfvénicity, which measures the correlation of the magnetic field and solar wind velocity fluctuations. However, the Helios spacecraft recorded high Alfvénicity slow solar wind at around 0.3 AU from the Sun, and the observations suggest this kind of slow solar wind shares similar characteristics as the fast solar wind. Following studies find the Alfvénic slow solar wind (ASSW) both at around 1 AU and in the inner heliosphere, and the results further indicate the ASSW and fast solar wind are similar in both macro and micro scales, implying the ASSW should also originate from the coronal holes. Additionally, the latest Parker Solar Probe (PSP) spacecraft has observed prevalent ASSW in the inner heliosphere, suggesting the ASSW could contribute to the network of slow solar wind. However, contradictory conclusions on the origin of ASSW are implied by different works, the reason could be the choice of different observations and/or the different methodologies. We note that most of previous works associated with the ASSW are mainly focused on the comparisons of different solar streams with several selected intervals or limited dataset, and there still lacks a comprehensive study of the ASSW with large dataset through different solar cycles to uncover the distributions, evolutions, and origins of the ASSW. Therefore, it is greatly valuable to investigate the ASSW over multiple solar cycles with multiple datasets. In this project, we want to focus on the following aspects:

" Distributions. We will identify the ASSW intervals in different solar cycles and build a large dataset with several spacecraft observations with a powerful machine learning technique. This dataset can give global distributions of the ASSW over several solar cycles. In this way, we want to show how the solar activities control the large-scale variations of ASSW with less uncertainty, and to identify how much the ASSW contributes to the slow solar wind at different phase of solar cycles.

" Evolutions. The Alfvénicity of solar wind will reduce with distances, so we observe less ASSW at 1 AU. Therefore, it is worth to investigate the radial evolutions of the ASSW.

" Origins. The limited dataset and different methodologies in the analysis of ASSW may bring uncertainties to identify the origins. Therefore, based on the large dataset, we plan to use both multi-event study and statistical method to compare the properties, especially the compositional signatures, of highly ASSW with other solar winds. Moreover, we will use the Potential-Field Source-Surface (PFSS) model to trace the ASSW back to the Sun. Combining the observations and model results, we want to figure out the origins of ASSW.

MISSION DATA: We will use the in-situ data from the Helios, Ulysses, Wind, ACE, PSP and Solar Orbiter. The combinations of multiple datasets over several solar cycles from the inner heliosphere to 1 AU can help study the ASSW thoroughly.

METHODOLOGY: Using the Helios, Ulysses, Wind, ACE, PSP and Solar Orbiter observations, we will first identify the intervals of the ASSW with machine learning technique. In the following, we will investigate their properties and distributions with solar cycles. Then, we will compare the inner heliosphere observations with that at 1 AU to figure out the radial evolutions of the ASSW. Moreover, we will trace the ASSW back to the source regions with PFSS model. Finally, we will combine the model results with the compositional signatures to identify the origins of ASSW.

RELEVANCE: The proposed works on the Alfvénic slow wind over multiple solar cycles are highly relevant to the Focused Science Topics of the Living With a Star Science: Understanding the Large-Scale Evolution of the Solar Wind throughout the Heliosphere through the Solar Cycle".

Bernard Jackson/University Of California, San Diego
A Holistic Solar Cycle Approach to Heliospheric Evolution from UCSD 3-D Reconstructions Using Thomson Scattering Data from STEREO HI and SMEI Imagery, and Interplanetary Scintillation Observations

From the year 2000, UCSD's time dependent three dimensional (3-D) reconstruction program has characterized the topology throughout the inner heliosphere based on interplanetary scintillation (IPS) observations. Now also incorporating Solar Mass Ejection Imager (SMEI), and STEREO Heliospheric Imager (HI), imagery and available in-situ measurements from any spacecraft, we have worked to combine all of these observations into a super-program" analysis system. This takes advantage of the benefits of each data source to provide plasma densities, velocities, and extrapolations of solar surface magnetic fields. Our Japanese colleagues have gathered much information about background global solar wind properties in the inner heliosphere using IPS analyses over two solar cycles. However, until now there has not been an attempt to reconstruct the propagation of rapid time variations much beyond Earth's orbit. Here we propose to rectify this and use our comprehensive 3-D reconstruction program to map structures globally to extend the recent science from Mars out to Jupiter. This effort is enhanced by ingesting these tomographic inputs into 3-D MHD modeling using ENLIL, so that now more of the known plasma physical properties are included to this solar distance.

From the UCSD Thomson-scattering SMEI and STEREO HI 3-D reconstructions of densities with about one hour cadence and few-degree latitude and longitude spatial resolutions near Earth and at STEREO, we have found that the heliosphere at 1 AU is not as simple as many modeling efforts imply. Our analyses show that CME fronts at 1 AU are highly corrugated and patchy; some have wavy fronts, and inhomogeneous structure. In-situ measurements can be adequately reproduced at a one-hour cadence, but nearby densities can be greatly different. This feature of the heliosphere, and the science of the small-scale propagation of switchback" fields and plasma, has become more evident from recent Parker Solar Probe (PSP) analyses. We do not know if such corrugation is a ubiquitous feature in all solar wind features - solar interaction regions (SIRs), shock processes, or the background solar wind. We assume that some smoothing occurs, and that the solar wind in general becomes more homogeneous at the distances probed by Ulysses; this proposed effort will clarify this using our highest resolution data sets.

For this FST #3 effort, we will use archival SMEI, STEREO, and IPS data (from the year 2000) and will employ all extant NASA in-situ plasma monitors as input, and verification checks to beyond Jupiter's orbit. This will allow better scientific comparisons all the inner planets to Jupiter, and at the asteroids in between. We note that most members of our group are Co-investigators on NASA's Polarimeter to Unify the Corona and Heliosphere (PUNCH) Small Explorer (SMEX) mission; when remote-sensing data from PUNCH becomes available, and with agreement from NASA and members of the FST, we will incorporate these additional data into the tomography. Our analysis goals set out below will:

1) Assess the 3-D tomography data sets over time to determine the best IPS, SMEI, and STEREO HI imagery sets to use at different times. These optimal data combinations throughout the solar cycle will then be used as inputs to the ENLIL 3-D MHD model to augment the solar wind interaction science out to the distances of the two nearest planets beyond Earth's orbit.
2) With our new understanding that CMEs and presumably most solar wind structures are spotty or at least corrugated from near the Sun to Earth, we will refine the scale of this variability, and its change with solar distance, in our most highly-resolved data sets.
3) Where CMEs are first observed in the LASCO or STEREO coronagraph images by FST members, we will track them until they are measured in situ at Earth, Ulysses, STEREO, and more recently at PSP, Solar Orbiter, and BepiColombo, out as far as Mars, and Jupiter.

Guiping Liu/University of California, Berkeley
Impacts of atmospheric planetary-scale waves on the equatorial ionosphere

We propose to systematically investigate where and how tides and planetary waves from the lower atmosphere drive the longitudinal structures and day-to-day variations of the low-latitude ionosphere. Tides, such as DE3 excited by latent heat release in the tropical troposphere can propagate upward to the lower thermosphere, where they modify the wind-driven dynamo electric fields causing the ionospheric four-peaked structures. Although most planetary waves are trapped in the middle atmosphere, they may still extend their influences into the ionosphere. By modulating tides, the multi-day periodic signatures associated with planetary waves could be carried to high altitudes. In addition, fast (short period) planetary waves, such as the 3-day waves may propagate to the F-region, directly driving variations in the density and height of the ionospheric F-layer peak. Through various pathways, the lower atmosphere forcing contributes significantly to the large-scale variability of the equatorial ionosphere.

Previous studies have identified tides and planetary waves in the E-region (~100 km altitude), but the vertical extents of these waves and how exactly they impact the ionosphere have not yet been determined due to lack of sufficient observations at higher altitudes. Here we will use newly obtained concurrent observations of both the atmosphere and the ionosphere from multiple data sources of ICON, GOLD, COSMIC-2, TIMED, Aura, COSMIC, and ground-based GPS that provide the necessary coverage. Our work will incorporate a systematic analysis of various tides (DE2, DE3 etc.) and planetary waves (2-, 3-, 5-, 6-day wave etc.) across a broad altitude range from ~90-300 km and simultaneously search for their corresponding signatures in the F-region ionosphere. These results will be compared to the simulation results from NCAR's Whole Atmosphere Community Climate Model with thermosphere and ionosphere extension (WACCM-X), including validating large-scale waves and their effects in the model. The WACCM-X results will be used to interpret the observed signatures and determine the processes responsible for tides and planetary waves to drive the ionospheric structures and variations.

Objective 1: Which tides and planetary waves are observed to strongly impact the equatorial ionosphere? At what altitudes do these waves exert their impacts on the ionosphere? We will analyze the observational datasets to identify each tide and planetary wave (characterized by period, amplitude, zonal wavenumber, vertical wavelength etc.) and the corresponding ionospheric structures and variations throughout multiple years from 2002-present. This will allow for identifying which waves and characteristics are influential. The ICON neutral wind data span both E- and F-regions, enabling observations of the altitude limits where these waves propagate.

Objective 2: Are there seasonal dependences for tides and planetary waves to strongly impact the equatorial ionosphere? What impacts do these waves have on the ionosphere at the solar minimum condition? These available datasets are adequate to identify tides and planetary waves and their ionospheric signatures in all seasons. Moreover, the ICON and GOLD data at the current solar minimum are extremely useful to examine the vertical propagations of these waves and their modifications on the ionosphere during quiet solar activities.

Objective 3: How do tides and planetary waves impact the structures and variations of the equatorial ionosphere? We will compare the WACCM-X simulations against the observations, and perform model runs with different resolutions and schemes to achieve the best model and observation agreements. We will analyze the model results to understand the pathways for tides and planetary waves to impact the ionosphere. Using controlled model runs, we will be able to quantify the contribution of each of the processes that are most significant to drive the ionospheric variability.

Mihailo Martinovic/University Of Arizona
Non-linear Solar Wind Turbulent Heating from 0.08 to 5.2 AU

Describing the heating of the Sun's corona and the expanding solar wind is a central problem of modern heliophysics. Several heating mechanisms have been proposed, each expected to operate under different solar wind conditions.
Recent results from Parker Solar Probe (PSP) have shown one particular non-linear mechanism - Stochastic Heating (SH), driven by magnetic moment invariance breaking due to turbulence, is increasingly effective at lower radial distances from the Sun. Examination of the proton Velocity Distribution Functions (VDFs) below 0.25 AU during PSP Encounters 1&2 confirmed theoretical predictions for VDF shapes to change from standard Maxwellian to flattop distributions, as SH tends to primarily heat particles slower than the VDF thermal speed.
In parallel, recent results based on Helios observations have demonstrated that the level of ion scale turbulent fluctuations---regarded as another clear indicator of SH activity---steadily decreases with radial distance, while also being enhanced in fast solar wind, more frequently measured close to the ecliptic around solar maximum. However, the Helios ion analyzers did not have the resolution required to confidently identify the VDF shapes. As the turbulence contains the information about in situ solar wind conditions along with traces of its evolution from the Sun, there was no conclusive way to distinguish if SH was operating at the point of measurement, or observed fluctuations are a remnant of the heating that happened days ago closer to the Sun.
In this project, we will use combined 45 years long survey of VDF and magnetic field data from Wind and Ulysses, enhanced with new high-resolution PSP and Solar Orbiter (SolO) measurements (available at CDAWeb and ESA Solar Orbiter Archive), to answer three crucial science questions (SQs):
1. How levels of SH in the inner heliosphere vary throughout three solar cycles?
2. Is the measured SH a genuine in situ process or a trace of near-Sun enhanced heating?
3. Is SH accompanied and/or affected by linear instabilities?
The proposed SQs are relevant to the FST Topic #3 Understanding the Large-Scale Evolution of the Solar Wind throughout the Heliosphere and through the Solar Cycle", its Goal #1 Utilize long-term measurements to quantify how the solar cycle impacts in situ plasma and magnetic field of the inner heliosphere" and Measurement of Success #2 Understanding and quantification of the impact of solar cycle variability on solar wind structures in the inner heliosphere".
To answer SQ1, we will extend the existing Helios SH analysis to Wind and Ulysses by using our already developed computationally efficient algorithms. These results will explain the solar cycle dependency of SH at various heliographic latitudes.
To understand if the estimated SH is happening in situ (SQ2), we will perform a statistical study of VDFs measured by Wind and Ulysses to estimate if they indeed exhibit flattop shape when SH is expected to be the dominant heating process. Some of the streams measured by Wind will be downstream of PSP and SolO, which will add another level of confidence as the large-scale statistical study will be enhanced by smaller multi-point case studies of tracked streams.
Finally, time-frequency analysis of turbulence will allow us to upgrade previous investigations of SH by differentiating low-frequency turbulent power that drives SH

from coherent wave power, and investigate how SH is connected to plasma stability (SQ3). Using well established PLUME and ALPS dispersion solvers, we will be able to understand the profile of linear instabilities raised in regions where increased SH modifies the VDF, and quantify the energy transferred back from particles to fields via instabilities.
The described research will provide a confident, reliable model of the solar wind heating, bringing us closer to overall understanding solar wind thermodynamics throughout the solar cycle and at varying distances and latitudes.

Jens Oberheide/Clemson University
Exploring the response of the ionosphere/thermosphere to the Madden Julian Oscillation

The overarching science goals are to explore and understand the global response of the ionosphere/thermosphere (IT) system to the Madden-Julian Oscillation (MJO) in the tropical troposphere, particularly ionospheric plasma and drifts. We will comprehensively analyze the MJO modulation of tides, Ultra-Fast Kelvin Waves (UFKW) and the mean in neutral and plasma parameters using a variety of spaceborne assets (ICON, GOLD, COSMIC-2, TIMED), ground-based observations (Poker Flat Incoherent Scatter Radar), and investigate the physical coupling mechanisms into the IT system using dedicated SD-WACCM-X and TIEGCM simulations, and MERRA-2.

The MJO is a recurring tropical weather pattern that shifts low-latitude convection patterns on intra-seasonal time scales (30-96 days). Recent progress in neutral dynamics data analysis mainly from SABER/TIMED and MERRA-2 has unequivocally revealed that the MJO impacts tidal and GW activity in the upper mesosphere (80-100 km) on the order of 10-20%, depending on latitude, season, and MJO location. Similar effects have been found in Kelvin waves and in thermospheric density from in-situ satellite measurements (i.e., GOCE). The new COSMIC-2, ICON and GOLD data allow us to make the next step and explore how the ionosphere responds to the MJO, a challenge that could not be met before due to a lack of data to resolve wave and mean variations originating from the lower atmosphere on weather timescales. Consequently, the MJO-modulation of the ionospheric plasma and drifts is not known to date. It is, however, likely that a strong response exists due to the MJO in tides, UFKW and GWs that either (i) impart the signal on the ionosphere through E-region dynamo or (ii) direct upward propagation and/or composition changes.

The ICON precession rate is fast enough to diagnose the tidal spectrum (period/wavenumber) with a time resolution ~1 month, which is sufficient to extract a MJO modulation of the tides in E-region winds and in F-region drifts & ion densities. This will be supported by high resolution SABER/TIMED tidal diagnostic and GOLD composition observations at constant local times. The COSMIC-2 constellation allows one to obtain the ionospheric tidal wave spectrum every day, e.g., using the hourly GIS data product, the radio occultation and in-situ observations. As such, we will be able to directly connect driving and response from the data. By nudging the observed E-region wind fields with/without MJO into TIEGCM, the model will be used to diagnose the propagation of MJO signals into the IT parameters such as vertical ion drifts and plasma density. Running SD-WACCMX with the MJO removed in the nudged MERRA-2 data will allow one to investigate the coupling mechanisms from the troposphere into the ionosphere through term analysis. Our study will also shed light into the physical coupling of the MJO into the high latitude ionosphere, to explain a surprisingly large MJO signal that we identified in a preliminary analysis of PFISR electron density observations.

The proposal directly addresses FST #1 as it will quantitatively connect an important and recurring tropospheric weather phenomenon with its impact on the IT system using new satellite data sets, ground-based data, and state-of-the-art models. All data are publicly available through the NASA SPDF, the COSMIC-2 data repositories, and the CEDAR Madrigal database.

Fabrizio Sassi/Naval Research Lab
A link between weather regimes: Large-scale teleconnections in the Earth s atmosphere and ionosphere

The extension of numerical models to the upper atmosphere (UA; thermosphere & ionosphere) with the inclusion of electrodynamics have produced high-fidelity whole atmosphere (WA) descriptions of the terrestrial weather, from the ground to the exobase (~500 km). Such WA interactions are mediated by traveling planetary waves, solar and lunar tides, and gravity waves that interact with the ionized atmosphere above about 100 km, and affect the structure and variability of what is called geospace weather. Thus, a link between the weather regimes of the lower atmosphere (LA; atmosphere below 100 km) and the UA exists. However, a holistic approach that includes both theory (numerical models) and observations (data assimilation), much needed to understand this connection, has been rarely implemented.
Forecasting the UA remains well behind predictive systems of the LA, due in part to compelling questions that remain unanswered: (a) what are the limitations due to forecasting errors; (b) what is the role of composition and transport to define the complex interactions between neutral dynamics and electrodynamics in the low latitude E-region; and, (c) can predictions in the UA benefit from a greater integration of modeling and observations with data assimilation techniques.
Our program focuses on large-scale interactions between the atmosphere and the ionosphere. The proposed research is articulated over four science objectives:
a. Does the seasonally changing large-scale energy propagation from the LA determine the day-to-day weather of the UA?
b. Are model errors of large-scale structures quantifiable using ensemble analyses/forecasts?
c. Are interactive composition and transport crucial to understand the large-scale low-latitude E-region electrodynamics?

d. Can the predictability of UA properties be evinced from initialized forecasts?
We will utilize a climate model (the Whole Atmosphere Community Climate Model, eXtended - WACCMX) either integrated with a data assimilation system (Data Assimilation Research Testbed DART) that includes observations in the UA, or nudged by atmospheric specifications (MERRA2; Modern Era Retrospective analysis for Research and Applications, version 2) up to about 65 km. The neutral dynamics produced by WACCMX will drive an ionospheric model (SAMI3 - Sami is Another Model of the Ionosphere) whose simulations are used to illustrate the effects of the neutral atmosphere on ionospheric dynamics, and the role of inline chemistry and transport that define the electrodynamics in the critical E-region. Observations from NASA space-based platforms such as GOLD, ICON, TIMED/SABER, and TIMED/TIDI, along with ionosonde measurements that describe the state of ionosphere, will be used to inform a data assimilation system in the thermosphere and to evaluate the forecast quality produced in both the thermosphere and ionosphere.
Ultimately, the project goals are to determine the role of the LA in the formation of the day-to-day weather of the UA, and quantify the predictability of their properties utilizing state-of-the-art tools and technique that integrate observations and theory.
Relevance: The proposed research addresses compelling questions for FST#1 in the LWS call that pertain to whole atmosphere interactions and predictions. In addition, the proposed study is directly relevant to the Decadal Survey Key Science Goal 2, Determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs."

Philip Scherrer/Stanford University
Toward a Consensus for Multi-Sourced Photospheric Magnetic Field Cross-Calibrations

Magnetic fields drive solar activity that ranges from long-term variability of the solar cycle to short-term eruptions of flares and CMEs. Consistent magnetic field measurements over the solar surface is the first step toward establishing reliable magnetic configuration and connectivity in the heliosphere enabling better understanding and prediction of solar activity.

Full-disk, line-of-sight (LOS) photospheric magnetic field has been measured for many years at various observatories, including MWO, GONG, KPVT, SOLIS, WSO, MDI, and HMI. While these measurements exhibit remarkable agreement in distribution and patterns of magnetic flux, appreciable difference has been found in their measured values. Difference in instruments, calibration, and data processing contributes to this. To produce magnetic field data over the entire solar surface, several issues also need to be addressed. Those include (1) polar field that is poorly obseserved, (2) magnetic field in the far-side where direct observation is not available to date and technology to infer magnetic flux remains to be made robust, and (3) deriving consistent radial field (Br) from LOS, or vector field. Accurate Br is the data many models of coronal and interplanetary fields use. Data from different observatories, together with different methods to deal with those issues, has led to significant discrepancy in model results. This seriously influences efforts to advance knowledge in understanding solar activity and its impact. Thus achieving consensus of magnetic field over the Sun's surface is vital.

We propose three tasks: 1) To seek a consensus for those magnetic field measurement cross-calibrations; 2) To derive synoptic maps of Br by addressing issues of polar field, use of far-side inferred flux, and conversion from vector and LOS data; and 3) To investigate the implied open flux problem by using our consensus field data in the photosphere.

We propose to employ a comprehensive methodology for this investigation. For task 1, we will use existing methods to examine the saturation correction, center-to-limb dependence of measurement, and spatial resolution of the data.
We will employ NSO's simulators of GONG and HMI extended to other instruments to validate and understand instrument differences. These will help develop cross-calibration between data from MWO, WSO, KPVT, GONG, MDI, SOLIS, and HMI.

For task 2, we will test existing schemes and develop new methods to correct polar field estimates. We will use observations and surface flux transport models to evaluate the methods. If it becomes available, we will also use SO/PHI to improve validation. We will examine impact of newly-emerging active regions on the far-side to the modelings by use of our recent O2R project that maps the far-side magnetic flux from helioseismic data. We will incorporate full-disk vector magnetograms from SOLIS and HMI to improve current model-dependent synoptic maps of Br. We will evaluate our final true synoptic (aka synchronic) maps by applying various models to the data and by comparing model results with observation.

For task 3, we will employ heliospheric models using final synoptic maps of Br and examine the modeled open flux with in-situ observations.

The proposed work cross-calibrates full-disk magnetograms taken by various observatories, provides consensus photospheric magnetic field over the Sun's disk, and produces reasonably reliable synoptic maps of Br. This work is relevant to the science goal from the Heliophysics Decadal Survey: to "Determine the origins of the Suns activity and predict the variations in the space environment". This is directly relevant to the objectives of the Focused Science Topic 4, "Towards a Quantitative Description of the Magnetic Origins of the Corona and Inner Heliosphere." The resulting data will be available to the other members of the LWS/FST as well as the world at large.

Peter Schuck/NASA Goddard Space Flight Center
The Origin of the Photospheric Magnetic Field: Mapping Currents in the Chromosphere and Corona

Science Goals and Objectives: Our science goal is to quantitatively determine the origin of photospheric magnetic fields. In particular, our goal is to distinguish between fields produced by currents in the solar atmosphere and the solar convection zone and to use this information to determine the magnetic origins of the corona and inner heliosphere. The photospheric magnetic field forms both the theoretical and observational foundation for understanding the structure, evolution, and eruptive potential of the solar atmosphere. Indeed, the magnetic field at the solar photosphere is a crucial input to both empirical and physics-based models of the corona and solar wind." Our objectives are to use this determination of the origin of photospheric magnetic fields to address the following fundamental science questions:

1. What is the origin of the photospheric field?

2. What is the non-potential state of the solar corona? Do active regions emerge with current? How common are partially dressed currents in the solar atmosphere?

3. How does the photosphere generate coronal non-potentiality?

Methodology: The PI has developed a sophisticated tool CICCI for distinguishing the coronal and chromospheric contribution to the photospheric magnetic field from the convection zone contribution with vector magnetograms. Preliminary work has demonstrated that a measurable fraction of the photospheric field in active regions is produced by current systems above the photosphere in the chromosphere and corona. This tool will be applied to a statistically significant sample of full-disk SDO/HMI vector magnetograms and a representative sample of Carrington maps and Hinode vector magnetograms to produce CICCI magnetic maps, with rigorous uncertainties, of the fingerprints of chromospheric and coronal non-potentiality in the photosphere. These tools will also be applied to simulations of both boundary driven energization of the corona and of dynamic flux emergence from the convection zone to the corona, for comparison with the results of the observational study.

Relevance to FST Science Objectives: This work directly addresses and impacts all three of the Focused Science Team objectives. (1) Understand how the magnetic field drives coronal and heliospheric structure and dynamics." Using CICCI magnetograms we will quantify the detailed development of the fingerprints of coronal and convection zone currents in the photosphere to ultimately characterize coronal and heliospheric structure. (2) Understand how magnetic connectivity evolves from the photosphere to the inner heliosphere." Using the CICCI radial fields we will determine the connectivity of the inner heliosphere with just the convection zone sources and compare this against traditional results using the total radial magnetic field. (3) Understand how plasma processes or time-dependent evolution lead to global non-potentiality." Using the CICCI decomposition we will determine the photospheric signature of chromospheric/coronal non-potentiality in both full-disk vector magnetogram observations and in a suite of flux-shearing, -cancelling, and -emerging simulations.

Potential Contributions to Team Effort: The evolution of the radial field produced by the convection zone determined by our CICCI analysis will prove useful to the FST team for modeling global solar and heliospheric phenomena such as surface flux-transport, fast versus slow solar wind acceleration, the structure of the global solar magnetic field, and the location of the heliospheric current sheet. Similarly, any boundary driven simulations of the corona or solar wind will benefit from the insight provided by CICCI analysis of the driven boundary. For global-scale modeling CICCI can provide the convection zone field in the photosphere which may be a better boundary condition for the heliosphere than the total field that conflates the convection zone and coronal current sources.

Yi-Ming Wang/Naval Research Lab
Constraining Solar Magnetograph Measurements Using the Observed Interplanetary Field and EUV and White-Light Coronal Images

Background

Reliable measurements of the photospheric magnetic field are essential both for a better physical understanding of the solar corona and for improved space weather predictions. Uncertainties in these measurements make it difficult to predict accurately the occurrence of high-speed wind streams and CMEs at Earth. Extrapolations of magnetograph measurements generally underestimate the interplanetary magnetic field (IMF) strength by factors of 2--4. In addition, we have recently shown that magnetograms underestimate the amount of minority-polarity flux inside active region plages and coronal holes, raising the possibility that ephemeral regions (ERs) may be a major contributor to coronal and solar wind heating.

Objectives

Our objectives are: (1) To understand why extrapolations of photospheric field maps tend to greatly underestimate the radial IMF strength (the "open flux problem"), focusing on the possible roles of Zeeman saturation, line weakening, zero-point calibration errors, open flux outside dark coronal hole areas, and transients/CMEs. (2) To develop procedures for modifying the magnetic synoptic maps so as to improve the agreement with the observed EUV and white-light coronal structures, as well as with in situ measurements of IMF structure and solar wind variations. (3) To determine whether the rate of ER emergence inside active regions and coronal holes is sufficient to provide a major or even the dominant contribution to coronal heating.

Methodology

(1) Using correlation analysis, we will compare the open fluxes, dipole strengths, and total fluxes derived from MWO, WSO, KPVT/SPM, SOLIS, GONG, MDI, HMI, and SPOT synoptic maps with each other, and the open fluxes with the observed radial IMF strength (from OMNIWeb, PSP/FIELDS, and SO/MAG). Agreement between the total fluxes measured by different observatories does not imply that their dipole strengths and open fluxes are in agreement, and a major source of the open flux problem may be errors in the dipole strengths. An important new idea to be examined is that the measured field strengths depend sensitively on where the magnetographs sample the line profiles. The contribution of CMEs will be estimated using the Richardson--Cane ICME catalog. (2) We will apply PFSS and PFCS extrapolations to the photospheric field maps to derive the configuration of coronal holes and streamers and compare the results with AIA, EUI, LASCO, SECCHI, WISPR, SoloHI, and Metis observations. The magnetic maps will be adjusted so as to improve agreement with the coronal, IMF, and solar wind observations, e.g. by adding or subtracting flux from the polar regions. This procedure will allow us to investigate systematic sources of error in the magnetograms and their dependence on the phase of the solar cycle. (3) Using AIA and EUI images taken in different EUV passbands, we will compare the looplike fine structure inside unipolar network and plages with that in quiet regions, to test the hypothesis that the rate of ER emergence is the same over the entire solar surface and independent of solar cycle phase.

Relevance to FST #4 Objectives and Potential Contributions to the Team

The objectives of this proposal are relevant to two of the main FST #4 objectives: "Understand how magnetic connectivity evolves from the photosphere to the inner heliosphere" and "Understand how the magnetic field drives coronal and heliospheric structure and dynamics." Measures of success are the same as those suggested in B.5, Sect. 5.2 ("Improved modeling of the solar corona....") Our basic objective is to improve space weather predictions by identifying the main sources of error in magnetic synoptic maps.

The PI and Co-I will contribute more than 35 years' experience in using photospheric field measurements to understand better the physics of coronal holes, coronal streamers, IMF variations, and solar wind streams.

Chih-Ping Wang/University of California, Los Angeles
Understanding warm plasma cloak in the magnetosphere

Science goals and objectives:
The warm plasma cloak (ions of a few eV to hundreds of eV and bidirectional field-aligned) is one of the two major cold magnetospheric populations (the other one being cold plasmasphere) and it plays important roles in several key magnetospheric processes. There is an important aspect of plasma cloak ions that is missing from the previous

observational and simulation studies. It is quite often to observe large enhancements (up to a factor of 10) in the cold field-aligned ion fluxes (cloak ions and outflow ions) on a time scale of a few minutes to tens of minutes with a spatial extent of a few RE, and the enhancement can exhibit an energy-dispersion feature. This mesoscale enhancement shows a dynamic aspect of the formation of the cloak ions that have not been explored and understood. Therefore, the overreaching science goal of this study is to establish a better understanding of the strong mesoscale enhancements of the plasma cloak ions from observations and to investigate the responsible physical processes with global kinetic simulations. Our two objectives are: (1) Objective 1. Establish observational understanding of mesoscale enhancements of plasma cloak ions using THEMIS data. (2) Objective 2. Establish physical understanding of plasma cloak mesoscale enhancements using 3D global hybrid simulations.

Methodology:

Observation data: We will use satellite data from THEMIS (2007 to 2020) to investigate plasma cloak ions and outflow ions.

Observation Tasks: (1) Investigate each mesoscale enhancement of field-aligned cold ions observed by THEMIS and characterize its temporal variation (field-aligned type and energy-dispersion types), spatial extent, and the corresponding plasma sheet conditions. (2) Statistically determine the mesoscale enhancements of field-aligned cold ions according to their characteristics in energy-dispersion, field-aligned type, spatial extent, their dependences on MLT sectors and the plasma sheet conditions.

Simulation: We will use the 3D global hybrid code (ANGIE3D) developed at Auburn University to self-consistently simulate ion kinetic processes for the formation of H+, He+, and O+ plasma cloak in a realistic and dynamic magnetosphere. ANGIE3D has been used to study the ion dynamics within the Earth's magnetosphere.

Simulation Tasks: The proposed simulation runs will be conducted in two different ways: (1) Artificially specify and control the outflow ions. We will run simulations with factors controlling the ionospheric sources. And we will run simulations with steady and disturbed plasma sheet conditions. (2) Using empirical outflow models driven self consistently by the simulated magnetosphere. We will conduct two simulation runs, one with steady and one with disturbed plasma sheet, using the empirical outflow driven self-consistently.

We will conduct observation-simulation comparisons to determine which physical processes can contribute to the observed mesoscale enhancements of cloak ions.

Relevance: Our proposed study of the plasma cloak is directly relevant to the Focused Science Topic (FST) #2 Pathways of Cold Plasma through the Magnetosphere". Our goal is directly relevant to the goal of FST #2 make significant progress towards understanding and predicting the complex feedback between ionosphere outflows and magnetospheric plasma". Our two objectives are relevant to the objectives of FST #2 Provide a better understanding of the origin of the warm plasma cloak; and to understand the factors controlling these sources." Our results can contribute to the Science Team's effort to improve the characterization of cold plasma composition and distributions" and advance the self-consistent modeling of cold plasma processes and processes controlled by the cold plasma" Our study directly addresses a goal from Heliophysics Decadal Survey, Determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere".

Liang Zhao/University Of Michigan, Ann Arbor
Global Evolution of Solar Wind along Solar Cycles

Science Goals and Objectives

The variation of the Sun and the solar wind influence every aspect of the Heliosphere. Since the unusual solar minimum between cycle 23 and 24, the weakened solar activity level has been directly influencing the solar wind properties and the interplanetary magnetic field. How the Sun's weakening activity level affects the large-scale evolution of the solar wind throughout the heliosphere becomes a more crucial question than ever. To answer this question, we propose a 4-year research project to investigate the variation of the solar wind and the interplanetary magnetic field in responding to the changing solar cycle. This proposed project will directly address one of the 2021 LWS Focused Science Topics (FSTs): Understanding the Large-Scale Evolution of the Solar Wind throughout the Heliosphere through the Solar Cycle". Particularly, we will focus on the following scientific goals:

1) To understand the impact of the changing solar cycle on the long-term and large-scale evolution of solar-wind structures ;
2) To understand the impact of the changing solar cycle on the topology of the solar coronal magnetic field and the Heliospheric Current Sheet (HCS).

Data and Methodology
We will perform three different types of investigations, including data analysis, numerical modeling and Machine Learning (ML) / Artificial Intelligence (AI) prediction. Specifically, we will use solar wind and magnetic field data from instruments across the Heliophysics System Observatory (HSO): ACE, Wind, STEREO, SOHO, Hinode, Parker Solar Probe (PSP), and the observations of the joint ESA-NASA missions, Ulysses and Solar Orbiter (SO). We will utilize the Potential Field Source Surface (PFSS) model and the Current Sheet Source Surface (CSSS) model to track the coronal magnetic field from the Sun to the Earth. In addition, ML/AI techniques will be applied to the data to more objectively categorize the solar wind types and to predict the future behaviors of the Sun's magnetic field topology. In details, we will:

1) Utilize the long-term solar wind measurements to quantify how the solar-wind properties change responding to the changing solar cycle. Solar wind plasma in-situ properties will be examined and compared across different phases of solar cycles. We will use coronal EUV images to examine the evolution of the corona.
2) Apply ML/AI data analysis techniques to solar wind data to classify the wind types.
2) Connect the in-situ measurements of the long-term solar wind to the Sun by using PFSS and CSSS models, to explore the wind's coronal sources. We will examine the coronal origins of the solar wind with S-web (Q-map) calculated by PFSS, to investigate whether the winds are HCS/helmet streamer or pseudostreamer-associated.

3) Use the Sun's source surface synoptic maps (calculated by the PFSS) to examine the evolution of the HCS topology. We will investigate how the changes of HCS topology affect the solar wind structure. We will apply AI/ML techniques to predict the topology of the HCS, so that to predict solar wind structure.

Relevance and Contributions to the Focus Team Effort:
Our proposed work is directly related to one of the FSTs, Understanding the Large-Scale Evolution of the Solar Wind throughout the Heliosphere through the Solar Cycle. The outcomes of our project will provide: 1) a full picture of how the solar wind structure evolves in a large-scale in the recent three solar cycles. 2) A new view of how the HCS controls the equatorial solar wind in the heliosphere in a long-term. And 3) a new insight of how the changes of the solar corona affect the solar wind that engulfs the whole Helioshpere. The achievement of our science goals will be the key milestones in addressing this FST.

Living With a Star Strategic Capabilities (LWSSC21)
Abstracts of Selected Proposals
(NNH21ZDA001N-LWSSC)

Below are the abstracts of proposals selected for funding for the Living With a Star Strategic Capabilities (LWSSC21). Principal Investigator (PI) name, institution, and proposal title are also included. Thirteen (13) proposals were received in response to this opportunity. On March 28, 2022, four (4) proposals were selected for funding.

Spiro Antiochos/University Of Michigan, Ann Arbor
A Capability for Community Modeling of Solar Eruption Propagation and Particle Radiation

The University of Michigan in close partnership with NASA/GSFC and NWRA proposes to build and deliver to the CCMC the Strategic Capability SCEPTER (Solar Coronal Eruption Propagation to Earth with particle Radiation). SCEPTER will be built on four cornerstone models that the proposing team has developed and delivered to the CCMC over the past two decades: AWSoM a model for the background corona and heliosphere, EEGGL a model for solar eruption (CME/flare) onset and evolution, M-FLAMPA a toolkit for calculating energetic particle acceleration and transport along dynamic field lines, and AMPS a complete modeling suite for calculating either single particle or particle distribution evolution in time-varying E-M fields. SCEPTER will also be built on the unmatched record of success by the proposing team in delivering on schedule and as promised Capabilities to the CCMC, in full partnership with CCMC staff, and in making the models available to the community both through the CCMC and via a non-commercial open-source license for the source code on GitHub.

SCEPTER will meld these foundational models into one powerful capability with a single set of interfaces so that the user can select an eruptive event and study its complete life cycle including impact at Earth. To achieve this ambitious goal, we will make major upgrades to both the background and eruption models. We will add to AWSoM an innovative method that we have developed for aligning the magnetic field line and the fluid flow in the wind, so that the connectivity from the heliosphere to the Sun can be determined, thereby, enabling rigorous calculation of SEP fluxes along those lines. We will add to EEGGL options for initiating the eruption: by a TD fluxrope and by shearing flows and/or helicity condensation. The most dramatic upgrade for SCEPTER is that we will couple our widely-used model for flux emergence/cancellation with EEGGL. With this new model, EEG-2, SCEPTER will be truly transformational. It will allow the general community to study, for the first time, the pre-eruption energy buildup as determined by the physically self-consistent interaction of the photosphere/convection region with the corona. This new capability is also very timely, because the increased computational resources needed by the inclusion of emergence/cancellation match up well with the new dedicated allocations that the CCMC has received on NASA HEC architectures. In partnership with the CCMC we will develop interfaces and user manuals for running SCEPTER both at the CCMC's in-house resources and at the HEC Centers. To validate user results and achieve closure with NASA mission observations, SCEPTER will provide the tools to output from the simulations, synthetic data for all the relevant missions in NASA's Heliophysics System Observatory, including SOHO, STEREO, SDO, WIND, and ACE, as well as for PSP and SO when that mission data becomes accessible to the external community. To schedule and focus the model development we have selected four science investigations that we will perform and that will define the timing of the milestones and model delivery to the CCMC.

The SCEPTER program is clearly bold and ambitious, but the proposing team has all the science expertise and development experience for successfully carrying out this program. The PI Antiochos and Co-PI Gombosi have decades of proven leadership in both science and modeling advances. The Institutional PIs Karpen and Leka are leaders in observations and simulations of solar eruptions. SCEPTER build on the long-standing partnership between the three participating institutions and the CCMC in delivering major capability advances to NASA and the Heliophysics community.

Gian Luca Delzanno/Triad National Security, LLC
Beyond MHD: Flexible fluid-kinetic global geospace model

The objective of the proposed work is to develop a new capability that will enable new investigations aimed at answering a fundamental and yet so far unanswered question: What is the role of microscopic/kinetic effects on the large-scale dynamics of the Earth's magnetosphere?

In general, the new capability will enable investigations of many pressing questions in magnetospheric science. Specifically, we target questions centered around the physics of magnetic reconnection onset in the magnetotail, which is essential for better understanding and modeling of magnetospheric substorms, some of the most energetic phenomena that are key to space weather science. With minimal modifications, our new capability will also enable significant progress on understanding the processes controlling dayside solar wind/magnetosphere coupling.

The Earth's magnetosphere is a complex system comprising diverse particle populations interacting via processes characterized by several orders of magnitudes in scale separation between the kinetic and system scales. Despite remarkable progress over the past decade, all existing methods that attempt to go beyond a magnetohydrodynamics (MHD) description of the magnetosphere have significant limitations. The method proposed here promises to overcome the limitations of existing approaches by coupling a highly-accurate modeling framework built on MHD and leveraging decades of development, GAMERA, with a unique approach to solve the kinetic equations, called SPS, by means of a spectral expansion. The project involves including anisotropic pressure and Hall MHD physics in GAMERA, developing improved preconditioning and adaptive capabilities in SPS, and developing a coupled GAMERA-SPS framework that will be delivered to the Community Coordinated Modeling Center. Several verification and validation efforts will document the accuracy and efficiency of the new algorithm and its ability to reproduce observational data.

The proposal is strongly aligned with the solicitation and incorporates many of the requested Targeted Objectives. It achieves 'Improved modeling of reconnection and electron scale physics in general' by embedding the SPS kinetic solver into the large-scale global MHD model GAMERA. It develops 'Inclusion of Hall MHD physics' in GAMERA. It uses 'New approaches to solving the Vlasov-Maxwell equations such as moment expansion or spectral transform methods' and achieves 'Improvements to computational stability and efficiency, novel approaches to reduce computation demand without impacting the physics' through the SPS spectral approach that allows one to dial-up kinetic physics as necessary and hence reduce the computational load relative to a fully kinetic approach. It also performs 'Extensive validation of codes   metrics on code diffusivity, energy and momentum conservation, accuracy in solving equations, deviation from pure MHD, etc'. The proposal is also strongly aligned with the overall NASA Heliophysics Science Objectives. By developing new capabilities that include kinetic/microscopic physics in large-scale magnetospheric modeling, we enable investigations that 'Explore and characterize the physical processes in the space environment from the Sun to the heliopause and throughout the universe', 'Advance our understanding of the connections between solar variability and Earth and planetary space environments' and support 'Develop the knowledge and capability to detect and predict extreme conditions in space to protect life and society and to safeguard human and robotic explorers beyond Earth'.

John Dorelli/NASA Goddard Space Flight Center
Magnetosphere Aurora Reconnection Boundary Layer Emulator (MARBLE): Magnetosphere-Ionosphere Coupling on Multiple Scales

Understanding the connection between magnetospheric dynamics and the aurora has remained one of the most challenging problems in magnetospheric physics for the last fifty years. One of the more exciting developments in the last two decades was the discovery that dispersive Alfvén waves (DAW) play a significant role (comparable to quasi-static potentials) in accelerating magnetospheric electrons to energies capable of generating auroral arcs during periods of high auroral activity. DAW have also been invoked to directly connect collisionless reconnection physics to the aurora, with important implications for the relative timing between magnetotail reconnection onset and auroral substorm onset. Unfortunately, there does not exist a global magnetosphere code capable of modeling the physics of reconnection generated DAW and their coupling to the ionosphere. We propose to address this significant gap in our modeling capability by developing a new "collisionless Hall MHD" model in which frozen-in perpendicular ExB electron motion is self-consistently coupled to non-local electron and ion transport parallel to the magnetic field. The new computational model, MARBLE (Magnetosphere

Aurora Reconnection Boundary Layer Emulator), will be designed to couple to an existing global Hall MHD code for the magnetosphere as well as a Fokker-Planck model for electron precipitation into the ionosphere. The new model will be capable of addressing the following science questions:

Q1. How does three-dimensional collisionless magnetic reconnection project to Earth's ionosphere?
Q2. How do reconnection generated field-aligned currents propagate to the ionosphere?
Q3. How is reconnection generated energy flux transported to the ionosphere?

MARBLE will be designed to run on clusters of Graphics Processing Units (GPUs) to enable reasonable simulation times for large magnetospheres with 5-10 cells per ion inertial length. Most of the development will occur on a dedicated 8 NVIDIA A100 cluster at NASA-GSFC. The same development environment will be available through an AWS cloud based interface provided by the Community Coordinated Modeling Center (CCMC) at NASA-GSFC. Our long term strategy will be to scale MARBLE up to larger clusters with thousands of GPUs.

Our proposed program will support two full time postdoctoral researchers with expertise in computational methods and machine learning to focus on: 1) the development of efficient numerical approaches for solving the electron and ion drift kinetic equations, 2) the use of deep learning to develop surrogate models for the propagation of input parameter uncertainties to quantities of interest.

MARBLE will be released under the NASA Open Source Agreement v1.3 and distributed in a NASA public github repository. In parallel, we will work with the CCMC to make MARBLE available to users through their Runs on Request web based interface. We will coordinate with the CCMC to ensure that we are meeting computational, storage, I/O, visualization and post-processing requirements at all stages in MARBLE's development. We will also work closely with the CCMC to establish a community driven model validation approach using both standard computational benchmarks as well as spacecraft and ground observations. This validation plan will promote an open science approach, with collaboration, transparency and reproducibility as core values. Several MARBLE community workshops will be organized during the course of the program.

Jon Linker/Predictive Science Inc.
DYNAMCS: A DYNAmically evolving Model of CMEs and SEPs

Coronal mass ejections (CMEs) are remarkable displays of solar variability, and are the leading cause of space weather effects at Earth. Major solar energetic particle (SEP) events are closely associated with CMEs. Measurements of the Heliophysics System Observatory (HSO) provide us with an unprecedented view of CMEs and SEPs. Exploiting these data to further our quantitative understanding of these fundamental phenomena requires advanced physics-based models. Such models can also become prototypes for eventual operational space weather models. We propose a four-year program to create a DYNAmically evolving Model of CMEs and SEPs (DYNAMCS) and deliver it to the CCMC for runs-on-demand. Our proposed program strongly leverages and builds on our present modeling capabilities from MAS/CORHEL and EPREM/EMMREM.

Our first major goal and delivery milestone is to seamlessly link ambient corona/solar wind, CME initiation, and SEP acceleration/transport models to produce comprehensive simulations of CME-SPE events for runs-on-demand.
Recognizing that the notion of a quasi-steady background corona that is perturbed by an event is too simplistic for many real-world situations, our second major goal and milestone is to deliver an evolving background coronal and solar wind magnetohydrodynamic (MHD) model, capable of running continuously, to the CCMC. This model will be driven by magnetic maps that assimilate available magnetograms and farside data to continuously update the ambient structure of the solar corona and inner heliosphere.

Finally, as the effects of multiple flares/CMEs are poorly understood, yet may have important space weather consequences, our third goal/milestone is to allow multiple eruptions to be introduced into the continuously-running model, providing a near-real time description of the solar corona and inner heliosphere.

When completed, DYNAMCS will address key target objectives, including:
(1) Combining data assimilation and simulations
to successfully span multiple spatial scales and improve the understanding of CME evolution in the corona and inner heliosphere;
(2) Incorporating new capabilities to study the evolution, magnetic properties, and substructure of CMEs as they transit the corona and inner heliosphere and interact with the solar wind;
(3) Incorporating new techniques or simulation capabilities that can eventually lead to improved forecasts of the space weather impact on the Earth system as a result of improved understanding of CMEs and their evolution through the corona and inner heliosphere; and
(4) Providing a broad combination of models and observations for detailed understanding of the propagation of CME/flare-generated particles from the Sun to 1 AU.

DYNAMCS will provide post-processing of the results for innovative diagnostics and validation, so that fundamental science questions can be addressed, including:
(1) How does evolution of the ambient corona and solar wind affect CME evolution, propagation, magnetic-field properties, and geo-effectiveness?
(2) How does this evolution affect magnetic connectivity in the inner heliosphere and the subsequent propagation of SEPs?
(3) How do multiple eruptions affect CME evolution, propagation, magnetic-field properties, and geo-effectiveness?
(4) How do multiple eruptions affect SEP acceleration and transport?

These questions are relevant to the three Heliophysics Science Objectives: (1) Explore and characterize the physical processes in the space environment from the Sun to the heliopause and throughout the universe; (2) Advance our understanding of the Sun's activity, and the connections between solar variability and Earth and planetary space environments, the outer reaches of our solar system, and the interstellar medium; and (3) Develop the knowledge and capability to detect and predict extreme conditions in space to protect life and society and to safeguard human and robotic explorers beyond Earth.

Space Weather Science Application Research-to-Operations-to-Research
ROSES-2021
Abstracts of selected proposals
(NNH21ZDA001N-SWR202R)

Below are the abstracts of proposals selected for funding for the Space Weather Science Application Research-t-Operations-to-Research program. Principal Investigator (PI) name, institution, and proposal title are also included. Fourteen (14) proposals were received in response to this opportunity. On October 12, 2021, 6 proposals were selected for funding.

Leka, KD /NorthWest Research Associates
A Bigger Library with Solid Bookends: Improving Solar Flare Prediction by Expanding Forecast Breadth and Addressing First/Last/Limb-Flare Challenges

Solar flares are directly responsible for some aspects of Space Weather, and can indicate other impending phenomena (Coronal Mass Ejections and Solar Energetic Particle Events). Predicting solar flares is challenging due to the remote-sensing nature of relevant data, unknown underlying physics, and the stochastic aspect of flare behavior. Even with almost an activity cycle of data from the Solar Dynamics Observatory plus another from the Solar and Heliospheric Observatory -- from a statistical standpoint (especially for large events), the sample sizes are smaller than optimal.

Probabilistic flare forecasts, and in particular the present operational facilities, generally perform with positive skill (Leka+ 2019), but are far from performing ""well"". Two very clear gaps in performance were recently identified (Park+ 2020). First, the ""first-flare / last-flare"" failures, or inability to identify when a region is going to become flare-productive, and then when it will become less of a threat; these scenarios are a large source of forecast ""misses"" and ""false alarms"" respectively. Additionally, flares that occur near the visible limbs can still impact the lower ionosphere, but pose a clear problem to operational flare forecasts. These shortcomings directly translate to less accurate ""All Clear"" forecasts.

We propose here to address the second focus area, ""Solar Flare Activity Forecast"" and improve skill of probabilistic flare forecasts by mitigating the two shortcomings described above. To address the ""first/last"" challenge, we will evaluate how quantifying active region evolution can predict when flaring activity will begin or end. To address the ""limb flare"" challenge, we will incorporate information from the far side of Sun using the Advective Flux Transport (AFT) model (Upton & Hathaway 2014) and helioseismology-based detections of new active regions and estimates of far-side active region magnetic flux. The research on improved forecasting will utilize the NWRA Classification Infrastructure (NCI), the research arm of the operationally-running RL 6+ NWRA Discriminant Analysis Flare Forecasting System [DAFFS; Leka, Barnes &

Wagner 2018] which is a potential platform for future transition of success from the proposed effort. Industry participation from NASA / Space Radiation Analysis Group will guide the effort.

The research will address two science goals: first, identifying those evolutionary patterns which identify both the start of flaring activity by an active region and the cessation of flaring activity, and second, verifying the ability to use far-side helioseismic results as input to flux transport maps (the seismic signal to magnetic flux and complexity mappings). The expected forecast enhancements will include improved skill overall and in particular for ""first-flare / last-flare"" and limb events. In addition to standard peak-Soft X-Ray flux-based probabilities, we will defined events according to duration, and provide probabilities for standard 1-, 2-, and 3-day forecasts as well as shorter 6-hour validity periods. Standard flare forecasting evaluation metrics will be invoked (Brier Skill Score, True Skill Statistic, ROC plots and Gini Coefficients, Appleman skill scores) as well as the radar-plot evaluations as presented in Park+ 2020, specifically designed to evaluate the challenges listed above. Improvement will be documented against published benchmarks.

The proposed effort is relevant to the second focus area because it will (1) enable more accurate solar flare predictions and All Clear forecasts by addressing known shortcomings, and (2) provide insight into the transition from quiet- to flare-productive as active regions evolve. As such, the proposed effort will answer both NOAA's goal of providing accurate operational space weather forecasts and addressing specific science questions relevant to NASA's research program to understand the Sun and the source of its variability.

Li, Gang /University Of Alabama, Huntsville
Forecasting Solar Energetic Particle Events at the Cis-Lunar Environment using the combined AWSoM-iPATH model

We propose to develop an operational Solar Energetic Particle Forecast model for the cis-lunar environment by combining the AWSoM model, which will be used to model a CME and its driven shock, and the iPATH model, which will be used to compute the time intensity profiles and particle spectra at the Moon. An user-friendly front end will be developed so that the combined suite is more suited for operational need. Our proposal addresses the first focus area of the solicitation: ""Cis-Lunar Environment Forecast: Develop improved space weather application models and operational forecasts for the cis-lunar domain as it pertains to increasing government and commercial activity."" The model will provide ""key particle parameters, such as the time dependent flux, maximum flux, event duration, and spectral characteristics of solar particle events"".

The AWSoM model is an MHD code that has been used extensively in the heliospheric physics community in modelling both the steady-state solar wind and coronal mass ejections. The simulation domain of AWSoM extends from the upper chromosphere to the corona and inner heliosphere (often below 30 Rs). By using a physically consistent treatment of wave reflection, dissipation, and heat partitioning between the electrons and protons, the AWSoM has demonstrated the capability to reproduce high-fidelity solar corona environment. The CMEs is initiated using the analytical Gibson-Low flux rope description. To determine the GL flux rope parameters, we use the Eruptive Event Generator Gibson-Low module that was recently developed to calculate GL flux rope parameters through a handful of observational quantities so that the modeled CMEs can propagate with the desired CME speeds near the Sun. As the CME propagates out, plasma parameters from the AWSoM code will be saved and fed into the iPATH model.

The iPATH model consists of three modules. The first module is a shock and plasma module which follows the propagation of the CME. In the current iPATH model, this module is constructed with a ZEUS2D code. However, the ZEUS2D cannot provide an accurate description of the CME and its associated shock below 10 Rs. In our proposed work, this module is replaced by the AWSoM model, which can follow the eruption of the CME from the corona. The second module of iPATH computes the accelerated particle spectra at the shock front. Energetic particles downstream of the shock can convect with the shock and diffuse. Convection and diffusion are followed using a 2D cell model in the second module of the iPATH. Upstream of the shock, energetic particles can escape and propagate to 1 AU before the shock arrival. This is treated in the third module of iPATH, where the focused transport equation is solved using the backward stochastic differential equation method.

Modifying the cell model to use the AWSoM model outputs of plasma parameters downstream of the CME shock is the major proposed task of this proposal. Besides modifying the AWSoM and the iPATH codes, a user friendly front-end will be developed so that the entire package is more suited for operational needs. The model will run under two modes. In the first "forecasting" mode, a continuous forecasting will be made using inputs from magnetogram only and which updates every 8 hours; in the second "interactive" mode, users will be able to alter a set of input parameters and examine how these parameters will affect the forecast. We will test and validate our model using past SEP events. One unique feature of the combined AWSoM+iPATH model is its capability to investigate particle acceleration when the coronal mass ejection (CME) and the CME-driven shock are still close to the Sun. This is critical to examine high energy particles (>100 MeV/nuc) in SEP events since most of these particles are accelerated close to the Sun, often below 5 Rs.

Martens, Petrus /Georgia State University
Operationalizing Data-driven Prediction Tools for Post-eruption Solar Energetic Particles

We propose to develop a novel, data driven, near real time (NRT), Solar Energetic Particle (SEP) event forecasting system for use in cis-lunar space by the NASA Artemis program, NOAA, and the DoD. We will integrate existing Machine Learning (ML) forecasting modules with those already functional or under development by our group into a fully tested and trained, seamless operational forecasting system that can be delivered without further ado to NASA/SRAG, NOAA, CCMC, and the DoD. We will develop and test our forecasting system with benchmark databases already published, maintained, and enriched by our group. Our system will be designed to operate on space and ground-based data that will be available, or are planned to be available, by NASA and NOAA in the Artemis timeframe, beginning in 2025. In order to produce NRT forecasts, our system will prioritize data sources with low latency between observation and data availability. Among other energy ranges, our main focus will be on the prediction of > 100 MeV time dependent proton flux, its integrated fluence, peak flux and event duration since these are the most important parameters that quantify the risk for astronauts and equipment.

Given the limited timeframe and budget limits of the SWR202R proposal opportunity, as well as the limited time left for our system to be put into operation before the return to the Moon, we have made the deliberate choice to base our system upon existing ML modules and benchmark datasets, as well as those in an advanced stage of development by our group. Specific predictions that we will deliver frequently and timely are the ""All Clear"" forecast with a prediction window of a couple of days, an ""Imminent Danger"" forecast with a window of hours, and a ""Warning"" forecast (with varying degrees of severity) with a window of days.

The performance of each of our system's modules will be fully verified and the modules will be optimized for an efficient 12-month transition that will be detailed into an envisioned Transition Plan by the end of the project's nominal two-year duration. The real life performance of our system will be tested against other methods operational at the time, using community adopted metrics, for which the NASA/CCMC scoreboards provide a convenient platform. At the expiration of the transition step, we will deliver our ready-to-go system to the CCMC and, if desired, to the DoD, NASA/SRAG, and NOAA/SWPC.

Some existing databases and ML methods that we will be using are:
- Our flare data benchmark for the SDO era, Nature: Physical Data, DOI:10.1038/s41597-020-0548-x
- Our flare benchmark for the EIT instrument, ApJS, DOI:10.3847/1538-4365/ab9a42
- A highly performing tree-based prediction method for SEP storms, IEEE, DOI:10.1109/BigData.2017.8258212

The system's core will be a two-tier forecasting system focusing on the Solar Proton Events (SPE) component of SEP events.

The system will rely directly on the potential solar sources of SEP events. We will be issuing an educated, executive decision on 'All Clear' or otherwise for the next 24 – 48 hours based on the monitored NRT solar magnetic activity. If an All Clear is not justified, we will be entering a probabilistic 'Watch' phase (in case of an All Clear, this probability will be 0) for the next 24 – 48 hours. This will be complemented by projected SPE temporal profiles, peak flux and fluence stemming from a comprehensive statistical and ML analysis of SPEs detected over solar cycles 23 and 24. We will be providing potentially critical information for future missions in the cis-lunar environment.

Our proposal is therefore squarely relevant to the first of the two application-oriented areas of focus of this B.7 SWR202R Call for proposals pertaining to the forecasting of a cis-Lunar environment forecast.

Munoz-Jaramillo, Andres /Southwest Research institute
Solar Flare Activity Forecast that takes advantage of 40 years of magnetic observations and machine learning

Flare forecasting is made difficult by the relative rarity of the events that matter (M and X-class flares). This means that a single instrumental era only has dozens of X-class flares (~40) and hundreds of M-class flares (~700 for the SDO era). Regardless of the approach, no single instrument contains sufficient statistics to take advantage of advanced machine learning (ML) forecasting techniques. We propose to develop a multi-cycle, multi-decadal application of deep learning to flare forecasting that takes full advantage of all magnetographs observing the solar magnetic field since 1976. We use a novel deep learning approach to sensor fusion to transform these heterogeneous magnetograph surveys into a common representation. We also perform robust estimates of deep learning uncertainty by training ensembles of neural networks, in a Bayesian approximation, delivering reliable flare forecast with well understood limitations. By being able to use magnetic measurements spanning 4 solar cycles we will be able to connect a wide range of solar magnetism with ~500 X-class flares and ~6,000 M-class flares – a full order of magnitude increase over solar cycle 24 (the SDO era) alone. We structure our project around the following objectives:

O1: Use deep learning to encode magnetograms belonging to six different surveys (1975-present) into a common representation tailored towards reliable flare forecasting.
O2: Train an ensemble of deep neural networks to produce a reliable 24-hour all-clear period forecast with robust uncertainty estimation.
O3: Train an ensemble of deep neural networks to enable a reliable flare class probability forecast with robust uncertainty estimation.

DATA:
We use public magnetogram data from the MWO (1967-2013), KPVT/512 (1976-1993), KPVT/SPMG (1991-2001), SOHO/MDI (1996-2010), GONG (2003-present), and SDO/HMI (2010-present), as an input to our deep neural network. We use F10.7 and X-ray flux time series measurements by the GOES satellites to provide context to our flare forecasts, as well as determining flare strength and all-clear intervals.

METHODOLOGY:
We set aside all observations during the last two months of every year since 1976 to test our algorithm under pseudo-operational conditions and keep it unseen and untouched until we are ready to escalate our readiness level (RL; see below). With the remaining data, (train+validation set) we train an ensemble of deep neural networks (NNs) to perform a probabilistic classification of daily magnetograms between all clear vs. flaring activity within the following 24 hours. We optimize the NNs for forecast reliability and use the ensemble to perform a robust estimate of uncertainty. We extend our NN

framework to make a probabilistic forecast of the ocurrence of M and X class flares for flaring days.

READINESS LEVEL CHANGE:
So far no forecasting effort has fully taken advantage of 5 decades of magnetograms, flaring activity, and advanced machine learning algorithms. Because of this, our project starts at RL 2: ""Applied research undertaken to determine new methods or ways of achieving specific and predetermined objectives". After the first 20 months we aim to achieve RL 3: ""systematic study to gain the understanding necessary to determine the means by which a recognized and specific need may be met". For this purpose, we use the test set containing data from the last two months of each year to test performance under pseudo-operational conditions. During the last 4 months of the project we work with NOAA's Space Weather Prediction Center to achieve RL 4: ""Validation of process in laboratory or other experimental environment".

Singh, Talwinder /University of Alabama in Huntsville
Forecasting Solar Flares Using the Time Evolution of Active Regions and Machine Learning Techniques

Accurate forecasting of solar flares is an area of active research due to their adverse impact on near-Earth space weather. Due to the availability of a large amount of solar data gathered over the years, machine learning (ML) can serve as an important tool for predicting solar flares. ML techniques have shown encouraging results in solar flare forecasting. Physical properties of active regions (ARs) obtained from their magnetic field observations or AR's magnetic, white-light, and EUV images, or both, are used as training data sets for ML algorithms.
However, ML-based studies that have been performed so far use time snapshots of various AR properties to do predictions. Solar flares are very dynamic events. A number of pre-flare processes have been discussed in the literature, e.g., the distance between the weighted centers of opposite magnetic polarities on each side of a magnetic neutral line (NL) where the flare occurs decreases and then increases before the onset of the flares. This shows that some pre-flare trends can be used for flare forecasting. Therefore, it should be beneficial to train ML models using the observed time evolution of ARs. This approach will have advantages over the existing methods, which use snapshots of derived properties and/or AR images at a given time. Some properties of ARs have also been shown to determine the eruptive and confined nature of solar flares, i.e., whether they will be accompanied by coronal mass ejections (CMEs). Therefore, ML models trained with CME/no-CME tags in addition to the flare/no-flare tag can potentially predict the occurrence as well as the type of the flares.
The objective of this work is to use machine learning for flare forecasting with the focus on the application of training data sets represented by time series of derived properties and images of ARs. In this work, we will use Geostationary Operational Environmental Satellite (GOES) solar flare catalog and Space-weather HMI Active Region Patches (SHARP) images and several AR parameters calculated from them to assemble a training database. The work will explore three primary ML approaches.

1) We will apply classical artificial neural networks and train our model with time series of various AR parameters. These parameters include some of the AR parameters provided with SHARP data, as well as a few other parameters that have been reported to show pre-flare signatures. In addition, we will use the flaring history of the AR as one of the training parameters because previously observed flaring has been linked to additional flaring from an AR. The major advantage of our approach is in using the pre-flare time evolution of these properties to make predictions.

2) We will explore using ML via convolutional neural networks (CNN), which have not yet been widely applied in the space weather domain, applied directly to still images (magnetogram/intensitygram/emission measure (EM) images), coupled with softmax activation functions in the CNN output to allow both an event/no-event forecast as well as the confidence level in the forecast.

3) We will explore using ML applied to intensitygram, magnetogram, and EM AR movies. This component is a highly novel aspect of the proposed work as it involves the utilization of recurrent neural networks (acting on CNN-detected image features), allowing one of the first use of movie sequences for training.

The three approaches will also be compared against each other, and other models developed, using true skill statistic (TSS) score, which has been shown to be the best for comparing the forecast performance of different models.

The proposed work will lead to an operational solar flare prediction tool and will answer scientific questions on the pre-flare dynamics in ARs. Therefore, this work is closely aligned with the objectives of the “Solar Flare Activity Forecast” area of focus of the SWR202R program.

Zhao, Lulu /University Of Michigan, Ann Arbor

Forecasting Solar Energetic Particle Radiation Using Data-Driven and Physics-Based Simulations

SCIENCE GOALS and OBJECTIVES:

Radiation hazards caused by solar energetic particle (SEP) events are great concerns in heliophysics and planetary exploration and the sparsity and large variations of the SEP events make them difficult to predict. SEPs are suggested to be accelerated either in magnetic reconnection-driven processes in solar flares or in the shocks that are driven by coronal mass ejections (CMEs) and all the large SEP events (>100 MeV flux greater than 1 p.f.u) are associated with fast CMEs. In order to provide reliable prediction, both the acceleration processes in the solar eruptive events (e.g. CMEs) and the subsequent transport processes in the interplanetary space need to be modeled. In this project, we propose to validate and deliver a ready-to-operate tool that runs faster than real-time to predict the properties of SEPs in the Cis-Lunar environment, utilizing data-driven and physics-based modules in the space weather modeling framework (SWMF). The SWMF is a high-performance computational tool to model the space-weather environment from the upper solar chromosphere through the interplanetary space to geospace. The real-time background solar wind plasma is modeled by the Alfven Wave Solar-atmosphere Model (AWSoM-R), which is driven by the near-real-time hourly updated GONG (or bihourly ADAPT-GONG) magnetogram. In the background solar wind, we will regularly (once a day, or even more frequently) launch real/synthetic CMEs using the Eruptive Event

Generator using Gibson-Low configuration (EEGGL), by inserting a flux rope estimated from the free magnetic energy in the active region. The acceleration and transport processes are then modeled self-consistently by the multiple magnetic field line tracker (M-FLAMPA) and the Adaptive Mesh Particle Simulator (AMPS). The four modules are fully integrated and run faster than real-time, thus providing a forecast capability.

EXPECTED FORECAST CAPABILITIES:
We will provide continuously prediction of the time intensity profiles of energetic particles above different energies (e.g. >10 MeV, >50 MeV, >100 MeV), the instantaneous and the projected event-integrated energy spectral index, the time when the flux corresponding to different energies cross the pre-set threshold, and the time when the flux decrease below the threshold.

METRICS and VALIDATION:
We will validate the model by simulating past events and comparing the simulated time-intensity profiles at different energies with the observations made by GOES, SOHO and the STEREOs. Other parameters, including the onset time, the peak intensity, the energy spectral index, the duration of the event, and those specified in the NASA/CCMC SEP score board can be derived from the time intensity profiles. We will also submit our model results to the SEP score board to allow the CCMC and SRAG console operator to evaluate our results against other models.

RELEVANCE:
The proposed work will provide a physics-based model to predict the probability and the post-eruption key particle parameters of SEP events, including the time dependent flux, maximum flux, the duration of the event and the spectral evolution. Therefore it is directly relevant to the area of focus of R2O2R: “Cis-Lunar Environment Forecast: Develop improved space weather application models and operational forecasts for the cis-lunar domain as it pertains to increasing government and commercial activity.”

Heliophysics Technology and Instrument Development for Science
Abstracts of Selected Proposals
(NNH21ZDA001N-HTIDS)

Below are the abstracts of proposals selected for funding for the Heliophysics Technology and Instrument Development for Science program. Principal Investigator (PI) name, institution, and proposal title are also included. Fourteen proposals were received in response to this opportunity. On January 19, 2022, five proposals were selected for funding.

James Clemmons/University of New Hampshire
Low-resource instrumentation for scientific measurements in planetary thermospheres

This proposal aims to improve the availability of global neutral wind measurements to study a variety of ion-neutral coupling phenomena, including winds associated with the equatorial ionospheric anomaly and thermospheric upwelling beneath the cusp. A number of mechanisms have been proposed as to the relationship between the strong structured winds in that region and the equatorial temperature and wind anomaly (ETWA), but more high-quality observations are needed to determine the exact cause. Similarly, there is a substantial density enhancement beneath the magnetospheric cusp that is associated with very strong winds. Modeling suggests that low-altitude observations are needed to understand this physical phenomena and why it strongly perturbs the winds.

This proposal focuses on miniaturizing two instruments for measuring in situ neutral winds in planetary atmospheres. The first measures the cross-track winds and the second the in-track winds. These instruments have been flown successfully on rockets, but the proposal aims to reduce them in size so they will fit in either a 6U or 12U cubesat, or another small satellite. This will be done by replacing a baffle wheel with a pair of deployable two-element baffles. Furthermore, the controller boards will also be redesigned so that they are much smaller in size.
Miniaturization will allow the sensors to fly on small-satellite missions, and potentially be included in constellations for greater fidelity localized neutral wind measurements than is currently achievable.

Jan Egedal/University Of Wisconsin, Madison
Exploring 3D Collisionless Magnetic Reconnection in the Laboratory

This proposal is to advance understanding of reconnection, a fundamental process in space plasmas that can release magnetic energy into flows and heating. The proposed research makes use of recent upgrades to the TREX experiment, which studies reconnection and related issues. TREX is unique in the world for studying collisionless reconnection and for its ability to access the regimes of plasmas relevant to reconnection in the Earth's magnetosphere. The proposal presents recently obtained experimental results which demonstrate the ability to experimentally characterize the electron scale structures of the collisionless reconnection regime. Through the construction of a 3D diagnostic suite applied to parameter scans at controlled and repeatable plasma conditions the experiment will provide complementary data to further the Science Goal of the MMS mission: to reveal, for the first time, the small-scale three-dimensional structure and dynamics of the elusively thin and fast-moving electron diffusion region. The science goals of this proposal are (1) To characterize the 3D structure and dynamics of the EDR, and (2) To document the parameter ranges including plasma beta, density asymmetry and guide magnetic field where the LHDI becomes active.

The proposed research will increase the number of magnetic and electrostatic diagnostics to fully characterize the 3D dynamics of TREX current layers. There are two main classes of proposed activities: (1) design and construction of specialized probes to address the science questions: new linear magnetic probes with teflon casing for 3D measurements; curved magnetic probes to match curvature of the electron diffusion region (EDR); and several arrays of "floating" electrostatic probes to measure fluctuating electric fields in the EDR. (2) several campaigns of discharges to record data, 150 discharges per day, for a total of about 5000 discharges. These experiments will measure background plasma parameters, the spatial and temporal variation of the current density and electrostatic potential, electron current layer width, and characterize the wave vector and frequency content, while varying plasma density, reconnection drive, background Helmholtz field, guide magnetic field, and fill gas. The experiments are proposed to characterize the 3D structure of the EDR, and determine where the LHDI significantly influences the dynamics of the diffusion region. In addition, kinetic plasma simulations will be used in a supporting role.

Solene Lejosne/University of California Berkeley
Development of Grotifer: a CubeSat for Three-dimensional Electric Field Measurements

The proposed work is motivated by the need for highly accurate 3D electric field measurements while enabling lower cost missions. In particular, the proposal argues that the electric field component parallel to the magnetic field needs to be measured accurately, since accurate measurement of the 3D electric field is important for the full electrodynamic specification of the ionosphere-magnetosphere system and is of relevance to several science questions. Some examples provided in the proposal are: 1. What is the importance of the parallel electric field in magnetic field reconnection? 2. How does the parallel electric field in the auroral acceleration region map to lower altitudes? 3. Are parallel electric fields important in the turbulent energy cascade in the solar wind? 4. What are the electric fields in the upper ionosphere and lower magnetosphere?

The proposal seeks to design, build, and test an engineering prototype of an electric field detector and central body attitude control system that can fit within a 27U CubeSat. The instrument accuracy is estimated to be 1 mV/m or better, and the distance from the spacecraft to the electric field sensor is required to be greater than 20 times the spacecraft diameter due to electric field contamination considerations (L/D>20). The proposed electric field instrument consists of two rotating plates, oriented perpendicular to each other (called Twin Orthogonal Rotating Platforms or TORPs) hosted on a non-rotating central body. Each of the platforms carries 4 stacer booms (5 m each) with wirebooms that then can deploy the electric field sensors further out (6.75 m). The proposed work has three main tasks: 1) Development and environmental testing of the TORP system, 2) Design an attitude control system that will maintain the central body fixed in inertial space while the TORPs rotate, and 3) Ensure that the electric field instrument based on TORP and the selected attitude control system can be housed by a 27U CubSat and meets the requirement so the instrument could, in the future, be proposed as part of a H-FORT proposal.

Samuel Tun Beltran/Naval Research Laboratory
An Imaging Polarimeter for Hydrogen Lyman-±

The proposal seeks to develop a novel detector for imaging polarization measurements of scattered solar Lyman-alpha for solar and geocoronal applications. Polarization signals result from interactions with anisotropic particle distributions (e.g. a narrow range of particle trajectories in a shock front) or in scattering, where the polarized intensity is dependent on the scattering angle (and hence the look direction). Polarized images of Lyman-alpha can measure the magnetic field in the corona along the line of sight through Hanlé depolarization. In addition, polarization images lend insight into the collisionless shock physics associated with CMEs. Finally, polarized scattered Lyman-alpha light from the Earth's geocorona serves as a diagnostic of the surrounding neutral H, which is coupled to the plasmasphere through charge exchange.

The proposal is to use a polarization filter directly deposited on back-thinned CCDs to map Lyman-alpha polarization over the image produced by an FUV optical system. This polarization filter is a wire grid polarizer (WGP), and consists of Au nanostructures with spatial periods below 100 nm. The WGPs reflect parallel-electric components of the light, while transmitting transverse-electric components, allowing a modulated signal to be measured. The proposers plan to begin their investigation by producing the needed patterns through deep UV (DUV) photolithography before transitioning to Electron-Beam Lithography (EBL), and to transfer the patterns into Au through either a lift-off process or reactive-ion etching (RIE) into underlying metal layers. A final stage involves writing pixel-aligned patterns onto a CCD to produce a prototype detector.

Xiaojia Zhang/University of California Los Angeles
High-Frequency Magnetic Loop for Heliophysics Exploration

The science objective is to investigate the magnetic component of solar and planetary radio emissions to help determine the generation mechanisms of solar radio bursts and planetary radio emissions. Most previous measurements of solar and planetary radio emissions have been limited to single-component electric fields by spacecraft wire antennas, or only to the high frequency part of the spectrum (above the ionospheric cutoff, >20 MHz) using ground-based instruments. However, little is known about the magnetic field component of these emissions, their polarization, propagation properties, and source dynamics of the main (<20 MHz) frequency range.

This instrument development effort will enable the operation of multi-small-satellite (CubeSat) high frequency magnetic loops (HFLoop) to measure the magnetic field components of solar and planetary radio signals. The specific methodology/technology goal for the investigation is to develop a 3D loop system that fits within a small satellite (CubeSat) and raise its TRL to 6 through environmental testing. Building off a single loop proto-type from France, the main engineering design task is to develop a stowage and deployment system for a three orthogonal 20 cm loop antenna system. Two key requirements for the proposed instrument are to be compact and deployable on CubeSats, and to have a sufficient sensitivity level, most preferably down to the cosmic background noise level. It should operate over a wide frequency range, from ~ 30 kHz to at least ~ 20 MHz. The proposal motivates measuring the magnetic component of the radio emission and contrasts it with the traditionally measured electric field as follows: (i) the 3D magnetic signal readily provides the k-vector direction and polarization of the waves (since divB=0 always), (ii) highly-sensitive loops can be much smaller (10-20 cm in diameter) and easier to accommodate and deploy than long electric wire antennas, and (iii) the proposed loops have sufficient sensitivity over a wide frequency range spanning both type II/III solar radio bursts and the aforementioned radio emissions at Earth and outer planets, allowing high quality spectral characterization and direction finding with a single instrument.

Heliophysics Low Cost Access to Space
Abstracts of Selected Proposals
(NNH21ZDA001N-HLCAS)

Below are the abstracts of proposals selected for funding for the Heliophysics Low Cost Access to Space program. Principal Investigator (PI) name, institution, and proposal title are also included. Twelve proposals were received in response to this opportunity. On March 31, 2022, four proposals were selected for full funding.

Bernard Jackson/University of California, San Diego
ASHI Instrument Image Analysis using Ground-Based, Extant NASA Spacecraft, and Balloon-Flight Images

We propose to ready the ASHI (All-Sky Heliospheric Imager) balloon flight instrument's imagery from a balloon flight, for scientific use and in preparation for a long duration spacecraft flight. The ASHI instrument (see Figure 1) was flown on a topside balloon flight on June 1, 2021. The ASHI system, largely unscathed through its balloon landing after cut-down from its 100,000 float altitude, has been refurbished, and is again invited to fly on a topside flight in the autumn of 2022. Here we propose to ready ground-based, extant NASA imagery, and the images from the refurbished balloon-flight ASHI, to provide a definitive basis for the science ASHI can do best.

ASHI addresses heliospheric science from the general question: What are the shapes and time histories of heliospheric structures, in two basic plasma parameters: density and velocity?" This has been studied to some extent in the same way from extant NASA spacecraft images using Solar Mass Ejection Imager (SMEI) and STEREO Heliospheric Imager data (for a recent review of SMEI analysis see Jackson et al., 2020, Frontiers, doi: 10.3389/fspas.2020.568429). However, we here concentrate on the ubiquity of the near-Earth structure observed in high-resolution 3-D reconstructions presented recently from SMEI and STEREO analysis, as heliospheric structures approach near and pass the spacecraft. From the Earth passage of the brightest CME structures in SMEI, we have found that CME density structures do not appear as a uniform front but have a corrugated or striated appearance. This differs from CME structures or their shocks, when presented by most 3-D MHD or kinematic model simulations, where the background solar wind and CME structure are both presumed uniform. If these corrugated shapes are ubiquitous to all types of solar structures, and are present in the less bright and less dense solar wind surrounding Earth, they have a profound implication for solar wind physics, and for that matter, Earth's solar wind magnetospheric interactions. The ASHI ability to 3-D reconstruct faint solar wind structures passing Earth will uniquely explore this science.

To enable the 3-D reconstruction of density starting from near the Sun, but especially events passing Earth, a key photometric specification for ASHI is 0.1% differential photometry in one-degree sky bins 90 degrees from the Sun. Although some aspects of the ASHI imagery concept have already been proven using extant SMEI and STEREO data, the ASHI instrument is a far more compact design than either of these previously flown instruments. We here extend this concept to include velocity; a heliospheric imager viewing Thomson-scattered light will yield high-resolution 3-D analyses of velocity as well as density that will be compared with in-situ measurements from spacecraft near Earth. This concept can be proven using the ASHI imagery from a topside balloon flight, but with less throughput than is ultimately envisioned for a spaceborne instrument. The ultimate ASHI to be proposed for a long-duration spaceflight promises to provide an order of magnitude improved light throughput over time than SMEI or STEREO, and can thus yield far better near-Earth 3-D reconstructions as well as velocity.

Christopher Moore/Smithsonian Institution/Smithsonian Astrophysical Observatory
The Swift Solar Activity X-ray Imager (SSAXI) Instrument for the Hi-C Flare Campaign

We propose to the NASA Low Cost Access to Space program to add the Swift Solar Activity X-ray Imager (SSAXI) Instrument as a ride-along to the already funded Hi-C Flare Campaign mission. The Flare Campaign is a high risk and high impact opportunity to observe a solar flare with multiple coordinated observatories including but not limited to: the Focusing Optics X-ray Solar Imager (FOXSI-4) rocket, the Daniel K. Inouye Solar Telescope (DKIST), Parker Solar Probe (PSP), and other current space observatories. The Hi-C Flare rocket will have a launch window spanning several hours a day, for several days at the Poker Flat Research Range (PFRR) in Alaska, until a large flare occurs for observation.

The SSAXI instrument has peak sensitivity to 10 MK solar plasma, similar to the current Hi-C flare instruments and provides exploration of additional parameter space, including the variability in heating and energy transport of solar flares. SSAXI combines X-ray focusing optics and a high speed readout detector to image the flare soft X-rays at a high time cadence without image saturation and pixel signal blooming into adjacent pixels. This allows an unprecedented opportunity to image large flare hot plasma unobscured, with high contrast imaging. The SSAXI ride-along concept will provide the groundwork for a future instrument on large satellite missions. SSAXI will address portions of the NASA Heliophysics Science Goal 1 Explore the physical processes at work in the space environment from the sun to Earth and throughout the solar system." By investigation the science questions:

SQ1: What is the relationship between soft X-ray pulsations and the continued heating into the decay phase?
SQ2: How does the spatial and temporal evolution of soft X-ray pulsations constrain the heating and energy transport processes in flares?

The SSAXI investigation will use numerical modeling, wavelet and Fourier analysis on the SSAXI data to constrain aspects of the flare heating and energy transport dynamics via the detected soft X-ray emission variability and quasi-periodic pulsations. The SSAXI investigation will train early career scientists, engineers, and students. The majority of the SSAXI science team are early career researches and there are plans for grad student and postdoc involvement on the SSAXI instrumentation team.

Marilia Samara/NASA Goddard Space Flight Center
Black and diffuse Aurora Science Surveyor

We aim to explore the processes responsible for creating the optical variations observable within the diffuse aurora, specifically targeting the physics responsible for the creation of black aurora. Such processes are critical to our understanding of the how, why and when energyexchange is modulated in the coupled magnetosphere ionosphere system. In order to study themin a meaningful way, the electron precipitation must be quantified inside regions of diffuse auroracontaining black aurora. Moreover, this has to be done with high-resolution, targeting millisecondtime-scales, in order to adequately capture the fine structure inherent in diffuse aurora. Therefore,an instrumented sounding rocket payload will be used to target diffuse aurora that contains blackaurora. A combination of in situ precipitating electron and magnetic field measurements will beused in conjunction with high-resolution ground-based imaging of the aurora, to investigate twospecific science questions:

1) What are the differences in the precipitating electron spectra (energy, flux, pitch-angle and temporal characteristics) inside and outside regions of black aurora?

2) What are the most likely physical processes responsible for generating the optical features of black aurora?

The scientific questions support NASA's Heliophysics Science Strategic Objective 1.4 to understand the Sun and its interactions with Earth and the solar system, including space weather" from the 2014 Science Mission Directorate Science Plan by addressing key concepts of energy transport within the coupled magnetosphere-ionosphere (M-I) system, which is an important component of how energy ultimately couples from the solar wind, through the magnetosphere and down into the ionosphere and thermosphere.

Amy Winebarger/NASA Marshall Space Flight Center
Marshall Grazing Incidence X-ray Spectrometer Reflight (MaGIXS 2)

X-ray spectroscopy provides unique capabilities for answering fundamental questions in solar physics. The soft X-ray (SXR) regime is dominated by emission lines formed at high temperatures, with untapped potential to yield insights into basic physical processes of the Sun and stars that are not accessible by any other means. The Marshall Grazing Incidence X-ray Spectrometer (MaGIXS) is a sounding rocket instrument developed as a pathfinder to acquire the first ever simultaneous spatially and high-resolution spectrally resolved X-ray observations of the solar corona in the SXR wavelength range.   MaGIXS was launched on July 30, 2021. Though MaGIXS successfully observed SXR spectra, several issues led to less than optimal data. Over the decade of MaGIXS development, the instrument evolved significantly. Most notably, the original MaGIXS slit was replaced with a slot. The alteration occurred late in integration, but we realized at the time that the removal of the requirement of an intermediate focus and slit implied that the optical design could be significantly simplified and many of the technological challenges that hampered the full success of the original MaGIXS concept would no longer be applicable.

We propose to rebuild the instrument with the simplified design and launch the MaGIXS-2 payload in April 2023. The new design can re-use the telescope mirror, grating, and several mechanical and electrical components from Flight 1. The MaGIXS-2 mission will address one of the fundamental problems of coronal physics: the nature of coronal heating. With its powerful set of plasma diagnostics, MaGIXS-2 will probe the high temperature coronal plasma and make four unique measurements to provide insight into this problem. For the last 20 years, solar astrophysics has imaged and measured solar plasma with extreme ultraviolet or ultraviolet instrumentation while taking broadband X-ray images with limited spectral information for measuring the temperature, density, or element fractionation for the various structures and events in the corona. As there has been essentially no SXR imaging spectroscopy of the solar corona since the Orbiting Solar Observatory days, there is a massive well of untapped potential for future discovery. The first flight of MaGIXS, occurring after a decade of technology and instrument development, demonstrated a revolutionary concept for grazing incidence imaging spectroscopy. The second flight will solidify and strengthen the technological investments put into the MaGIXS mission, will carry out a compelling scientific investigation, and will provide a full proof of concept for an X-ray Imaging Spectrograph that is planning to be proposed for a future satellite mission.

Heliophysics Flight Opportunities Studies
Abstracts of Selected Proposals
(NNH21ZDA001N-HFOS)

Below are the abstracts of proposals selected for funding for the Heliophysics Flight Opportunities Studies program. Principal Investigator (PI) name, institution, and proposal title are also included. Five proposals were received in response to this opportunity. On January 18, 2022, two proposals were selected for funding.

Xinlin Li/University Of Colorado, Boulder
Dual Cluster Mission Concept Study

The goal of this proposal is to conduct a mission concept study to determine the number of spacecraft and their optimal orbits, optimum instrumentation, costs associated with implementation options for a mission to achieve the stated science objectives. Specifically, the designed Dual Cluster mission will address the following science questions:

(1) What are the spatial and temporal scales of various types of electron precipitation (drift loss cone, precipitation bands, and microburst)?

(2) What is the total precipitation loss of the electrons and the relative contribution of the various types of electron precipitation?

(3) Which plasma waves are causally responsible for the various types of electron precipitation?

With particle instruments onboard multiple spacecraft at LEO, the proposal aims to address science question (1) and (2). Combining LEO measurements with measurements at GTO-like, the proposed mission will be able to address science question (3).

Rachael Filwett/University of Iowa
LabOratory for the Behavior of the SloT Region (LOBSTR)

The proposed effort will conduct a concept study for a mission known as LOBSTR (LabOratory for the Behavior of the SloT Region) to investigate the Earth's radiation belts, and in particular the slot region between the inner and outer belts. The proposed science questions target 1) the dynamics of electrons at the inner edge of the outer radiation belt; and 2) the dynamics of protons at the outer edge of the inner radiation belt. Science questions also aim to investigate the local time (MLT) dependence of these populations. Regarding question 1, the proposed mission will investigate the inner boundary for energetic electrons ("the impenetrable barrier") and the mechanisms responsible for this boundary, in particular radial diffusion and precipitation. Regarding question 2, the proposed mission aims to investigate the potential mechanisms for trapping solar energetic protons (SEPs), creating enhancements to the inner belt proton flux during geomagnetic activity. Additionally, the mission concept will study the MLT dependence of both electron penetration into the slot region, and solar energetic particle (SEP) trapping on the outer edge of the inner belt.

Heliophysics Data Environment Enhancements
Abstracts of Selected Proposals
(NNH21ZDA001N-HDEE)

Below are the abstracts of proposals selected for funding for the Heliophysics Data Environment Enhancements program. Principal Investigator (PI) name, institution, and proposal title are also included. 4 proposals were received in response to this opportunity. On November 17, 2021, 3 proposals were selected for funding.

Kevin Reardon/Association Of Universities For Research In Astronomy, Inc.
Feature Extraction Tools for Exploratory Analysis of Remote-Sensing Solar Observations
21-HDEE21_2-0003

The goal of the proposed effort is to provide users the means to seamlessly incorporate a selection of versatile data exploration and processing techniques into their Python-based workflows in heliophysics research. Remote-sensing solar observations are information-rich, multi-dimensional datasets, usually consisting of spatially, spectrally and temporally resolved measurements of the intensity and polarization of the emitted light. Having tools that allow specific features of interest to be identified, classified, tracked, and enhanced allows for better exploitation of those data. Such techniques can be used not only to assemble statistically significant sets of similar events that can be studied as an ensemble, but also to identify outliers and discover new phenomena in the solar atmosphere. The features to be identified can span one or more physical dimensions - spatial, temporal, or spectral. These tools will be applicable across multiple NASA missions (Hinode, SDO, IRIS) as well as an array of ground-based observatories obtaining coordinated observations, and even in support of in-situ missions like Parker Solar Probe.

Such methods have been developed and used in a large array of scientific studies that have provided new insight into the physics of the solar atmosphere, and a variety of Python implementations exist for some of the specific tasks related to image processing, machine learning, feature tracking, signal optimization, etc. A limited selection of these algorithms have been integrated into SunPy s sunkit-image framework, but there exist many more tools that the community could make broader use of if they were available through such a user-accessible framework. In this project, we propose to implement common interfaces allowing some of these tools to be used together on a range of solar imaging data. These may come from existing standalone Python tools, be ported over from programs available only in IDL, or be developed as new implementations if no method suitably tailored to solar data analysis exists. The project will involve: a) identifying key techniques that will provide the most value to the community; b) examining existing implementations of such techniques, in both Python and IDL; c) designing interfaces and implementations that allow their integration with SunPy and the PyHC environment; d) developing and distributing of open-source code that provides a straightforward, accessible toolkit to the users; e) producing documentation and tutorials to foster community usage.

Edmond Smith/Johns Hopkins University
Taming the Monster: GAMERA model access using Heliophysics Standards
21-HDEE21_2-0002

Global geospace modeling is now generating large volumes of data that can easily surpass data volumes from entire missions. One high-resolution simulation run of a geomagnetic storm can produce terabytes of data. Wide community access to this data is necessary for providing context for NASA missions, but also for expanding simulation data analysis beyond the modeling teams and thence expanding fundamental knowledge about outstanding science questions of Heliophysics.

The APL-developed global magnetosphere model, GAMERA, provides high time cadence (order 10 s) parameters across geospace including all regions of the magnetosphere, as well as parameters of ionospheric electrodynamics. We proposed to expand community access to GAMERA model outputs in two ways: 1) by providing a standard access mechanism for retrieving model values; and 2) by providing standard ways to extract simulated spacecraft data based on virtual fly-throughs of the model for major Heliophysics missions including Van Allen Probes, THEMIS, and MMS. While these two capabilities already exist in some form and are routinely used by the modeling team, the proposed effort will create a standard, Python-focused way of accessing the model data for the entire community.

GAMERA data is already made available to interested collaborators. We will expand this by eventually providing a cloud-based analysis portal through which the full model output data could be analyzed in the cloud (no need to download large volumes of model output and no need to get a supercomputer account to access the full data). Codes exist to access the model data, but these are using specialized interfaces. We will create a standardized access mechanism to model output using the relatively new Heliophysics Application Programmer s Interface (HAPI). HAPI offers a standard way to access time series data products, and GAMERA output can be viewed as a large set of data points at each time step. We will also use HAPI to expose simulated instrument data obtained by extracting model parameters along spacecraft trajectories throughout the modelled region.

GAMERA is part of a larger geospace modeling framework, the Multiscale Atmosphere Geospace Environment (MAGE). The results of this project will lay the groundwork for further expansion of the developed data-access tools into other domains of geospace and types of data (e.g., particle spectra in the inner magnetosphere or the auroral region, as well as the ionosphere-thermosphere parameters). Furthermore, GAMERA is also applied to modeling of the inner heliosphere. The work proposed here will automatically benefit all these additional domains of geospace and the heliosphere and provide community-wide access to the corresponding simulation data.

Leslie Woodger/Dartmouth College
BARREL Data Analysis Software for Python Users
21-HDEE21_2-0001

The NASA BARREL (Balloon Array for Radiation Relativistic Electron Losses) mission, a mission of opportunity to the Van Allen Probes mission, used instrumented high-altitude balloons to remote-sense electron precipitation from Earth s radiation belts over broad geographic regions. Each payload s primary instrument was a NaI spectrometer, which measured bremsstrahlung X-rays from precipitating electrons. Forty payloads were deployed in two Antarctic summers in 2013 and 2014 creating an array of slow-moving measurement stations. With the remaining spare 6 payloads from the original campaigns, additional balloon launches occurred from Kiruna, Sweden in 2015 and 2016, as well as from Antarctica in 2018 and 2019. During these flights, BARREL observed electron precipitation events with a wide range of energy, spatial, and temporal characteristics. Furthermore, BARREL balloons are found to be in conjunction with various complementary spacecraft such as Van Allen Probes, DSX, Arase, GOES and LEO satellites such as FIREBIRD and POES.

The data management plan for the BARREL project included processed CDF files and a suite of software for the community to use for ease and efficiency in plotting and analyzing the data. The software package was called BARREL data analysis software (Bdas), written in IDL, and was integrated into the THEMIS software package called SPEDAS. Multiple investigations have used this software to advance our understanding of radiation belt electron precipitation in published studies. More specifically, the BARREL data is valuable in addressing the following science goals:

1. Test wave-particle interaction theory by combining BARREL measurements of electron precipitation with simultaneous Van Allen Probe in situ wave, plasma, and energetic particle measurements.
2. Rank the importance of different classes of precipitation and their associated precipitation mechanisms from measurements at a range of magnetic local times and latitudes. The loss rate for different types of precipitation can be estimated and further quantified during periods of conjunctions with LEO satellites to determine their relative importance.
3. Explore high temporal and spatial structure within observed electron precipitation. These features can be compared to coherence scales of wave observations, to shed light on their underlying processes.

Since that time, the Heliophysics community has migrated from using IDL software tools for analysis to tools coded in Python. SPEDAS has already taken measures to transition its software over to the python platform as pySPEDAS. This proposal seeks support to transition the Bdas software into the Python language. Our efforts will work in accordance with the pySPEDAS software format such that at the conclusion of this project the new software will be included within the pySPEDAS software package. The Python BARREL software will have the same functionality as the Bdas software. Bdas included programs to plot all the different BARREL data files such as the X-ray data, GPS, and magnetic coordinates. A spectroscopy code was also developed as part of the

Bdas software which transformed X-ray energy spectra to electron energy spectra using a chi-squared fitting algorithm.
A transition of Bdas into Python and subsequently pySPEDAS will directly support the goals of the PyHC effort to minimize the community effort to duplicate and reproduce software required for investigations utilizing BARREL data. Furthermore, inclusion of BARREL software into pySPEDAS increases the efficiency of researchers to utilize BARREL data in conjunction with other spacecraft. Currently, pySPEDAS supports over 20 missions including Van Allen Probes, GOES, and POES. With the continued collection of electron precipitation data from the BARREL instrumentation in conjunction with multiple complementary spacecraft it is extremely important to continue to make it usable and accessible to the larger Heliophysics community.

Geospace Dynamics Constellation Interdisciplinary Scientists Program
Abstracts of Selected Proposals
(NNH21ZDA001N-GDCIDS)

Below are the abstracts of proposals selected for funding for the Geospace Dynamics Constellation Interdisciplinary Scientists Program. Principal Investigator (PI) name, institution, and proposal title are also included. Ten proposals were received in response to this opportunity. On November 16, 2021, three proposals were selected for funding.

Rebecca Bishop/The Aerospace Corporation
Atmospheric Data And mission Planning Tool in an Interactive Visualization Environment (ADAPTIVE)

One of the most difficult aspects of a constellation science mission is the organization, utilization, and visualization of data from different types of instruments. The purpose of the Atmospheric Data And mission Planning Tool in an Interactive Visualization Environment (ADAPTIVE) is to enable an interactive visualization of data that can be used to identify time, locations, and features of interest for use in focused investigations supporting GDC Goals and Objectives by all members of the science community. In addition, the tool will enable assessment of GDC sensors Field-Of-View (FOV) of coverage that may be used to assist in constellation configuration refinement and concept of operations (CONOPS) planning. ADAPTIVE will enhance GDC mission science data by also providing a 3-D visualization of the background ionosphere structure that the GDC sensor data can be overlaid that allows the user to interact with the map to focus on times and locations of interest. The background ionosphere will be created by applying tomography to a combination of available on-orbit science and commercial and ground-based TEC datasets. The global ionospheric map will directly support GDC Science Goal 2 and may be used by the GDC science team to support investigations such as conjugate ionospheric structures during mission design reference periods and different geomagnetic conditions.

Mission-specific tasks include:
" Refinement of constellation configuration by visualizing data types and coverage prior to launch
" Support of post-launch GDC CONOPS and general ground-based campaign planning with respect to ionospheric conditions throughout various phases of the mission
" Support planning of calibration, validation, and verification efforts by visualization of potential ground-based dataset with planned GDC datasets.
IDS-specific tasks include:
" Development of a tool to enable efficient use of the GDC and supplemental datasets through global visualization of disparate datasets.

"	Provide an animated visualization of the ionosphere and GDC data for public presentation and interactive use.
"	Provide a tool that can easily extract data of interest from an interactive animated visualization map and save them to a defined standard format for further study.

ADAPTIVE consists of four primary capabilities: 1) Tomographic reconstruction of the ionosphere to provide conditional context 2) Interactive 3-D animated visualization image of the ionosphere 3) Capability to overlay disparate data sets, 4) Selection of time and location on image and extraction of available data to a defined format for further study. The software tool will implement a node-based data flow system with nodes available to read, process, combine and visualize multiple types of datasets. Consisting of a combination of open-source software solutions, previously created imaging libraries, and custom software specific to this mission, the highly parallelized tool will allow users to set up an analyzation data flow, display results and interactively update settings, zoom into areas of interest, select/deselect items, as well as specify time windows. An expandable architecture will allow incorporation of other available dataset types (e.g. ground-based imagers, ionosondes, ISR) in the future as desired. The software will be created utilizing container architecture that will enable portability to different cloud hosting platforms.

The ADAPTIVE IDS team includes Dr. Rebecca Bishop as Principal Investigator and Mr. Tad Gielow as tool developer and animator. Dr. Bishop has extensive experience working with GPS and other in-situ ionospheric data and has participated in the planning and execution of numerous mission CONOPS and calibration/validation activities. Mr. Gielow has worked four years as a data visualization engineer at Aerospace and previously worked over thirty-five years producing motion picture visual effects and animation.

Yue Deng/University Of Texas, Arlington
Study of Multi-Scale Forcing Impact on the Ionosphere-Thermosphere system: Support from Physical Models and Observations

To contribute to the exciting GDC mission opportunity, we will utilize both physical models and observations to support the following tasks:

1. Mission-specified tasks:
1) Refinement of the constellation configuration and mission requirements.
We propose significant GITM simulation efforts utilizing different specifications of high-latitude electrodynamic forcing to inform what satellite configuration is needed to address the GDC science objectives. We will identify the critical spatial and temporal scales of forcing and I-T structures using ground-based observations and simulations. Those scales will inform what satellite separation and revisit time are required to resolve those important structures. Virtual satellites will be used to optimize GDC observations, identify limitations, and evaluate capabilities for addressing the GDC objectives.

2) Calibration, validation, and verification.
Our team has the expertise to help calibrate, validate and verify GDC measurements using com- plementary observations. A) Cal/Val: Incoherent Scatter Radars (ISRs) provide the ground truth of plasma temperature, plasma density and thermal ion velocity at 300-400 km altitudes. B) Verification: ASI, SuperDARN, GNSS TEC, FPI and other ground-based observations will provide measurements of multi-scale I-T variations over a large spatial domain with temporal evolution and will help verify the physical connections be- tween forcing and I-T disturbances.

4) Data products and formats.
Our team s modeling and data analysis experience can inform what data products are needed to fulfill the GDC science objectives and maximize the science return. Specifically, ionospheric con- ductance and Joule heating are critical parameters for achieving GDC science goals, but cannot be measured and are not listed as GDC primary and secondary parameters. They can be calculated with reasonable accuracy and precision by combining the measurements across the science pay- loads with realistic model simulations. Additionally, the altitudinal profiles of conductivity, Joule heating, and GDC primary/secondary parameters will be available from GITM simulations, which will provide a global context for the GDC observations. We propose to generate those new data products of community interests and overall GDC science significance..

2. IDS-specific tasks:
1) Analysis techniques and tools.
The team has developed many relevant techniques, including reconstructing 2-D TEC map using machine learning SNP-GAN model, estimating the neutral wind acceleration from observations and generating particle precipitation and local ion-convection maps from ground-based data.

2) Physical models.
GITM is the first 3-D non-hydrostatic general circulation model (GCM) for the upper atmosphere.

We will fundamentally improve its capabilities for multi-scale simulations through upgrading the grid structures, enhancing forcing specification and including meso-scale related physical pro- cesses. The coupling with ASHLEY, SWMF and ground-based observations will greatly enhance the specification of high-latitude forcing in GITM. Further model development will enable the transition of models for operational uses.

3. Impact:
The project aims to provide system-wide observations and modeling to improve the specification of the energy and momentum input into the I-T system, and to determine how the system responds to these input at different scales, which will be critical to support the mission plan- ning and operation, and to maximize the mission science return. We will create a new platform, Support from Observations and PHysIcs modEls (SOPHIE), providing an interface for the data injection, sharing simulations for virtual

satellites and global context from the modeling frame- work, and releasing the scientific software and tools to support the GDC mission.

Jeffrey Thayer/University Of Colorado, Boulder
Maximizing Scientific Return and Operations of the GDC Mission

This proposal addresses the need for Interdisciplinary Scientists (IDSs) to expand the Geospace Dynamics Constellation (GDC) mission science team, optimize operations of the mission, and maximize the scientific return. The proposed team consists of subject matter experts that have combined experience in ionosphere-thermosphere (I-T) science and modeling, data assimilation schemes, satellite mission development, data architectures and processing, satellite systems and instrument engineering, orbital and aerodynamic modeling in low Earth orbit (LEO), and engagement with science and operational communities. This talented team can help address unforeseen issues that arise during the Phase A-D process towards launch.

The team proposes four mission-specific (M-S) tasks to optimize GDC mission operations. One task will improve the mission requirements by assessing the methods for determining gradients and temporal variations in measured properties. A second develops validation capabilities and procedures that include the engagement of the broader space science community. A third task is to create a real-time GDC data architecture to benefit operational users. A fourth task addresses the management of data and its distribution to instrument teams and the community. These four M-S tasks will be completed in Phase A/B and Phase B/C portions of the mission development.

The team proposes an IDS-specific task to develop an analysis tool using a novel technique called Global Navigation Satellite Systems (GNSS) accelerometry to maximize the scientific return from the GDC mission. This technique has been demonstrated to work with standard GNSS signals from LEO satellites resulting in the retrieval of information about the thermosphere neutral density state. The use of such a technique on the GDC constellation will create a unique data set that can help with M-S tasks by providing an on-orbit validation of in-situ thermosphere measurements for each satellite over the entirety of the mission. It can also provide a new science capability by enabling the study of atmospheric drag on LEO satellites, which can have a broader impact on how future satellites operate in LEO. This will be a tool developed as an IDS-specific task (with M-S task connections) and will be provided to the GDC science community at the end of Phase D.

The team proposes a second IDS-specific task to advance I-T physics-based models through a unique data assimilation (DA) scheme for improved specification and forecast of the I-T system. The particular DA scheme specifically addresses how energy deposition from external sources of the I-T system cause an I-T response in its state properties. This is a central goal of the GDC mission and our approach will ensure a clear connection is made between measurements and physics-based models. This DA scheme coupled with a physics-based model will be shared with the GDC science community at the end of Phase D.

Completion of these M-S and IDS tasks will help ensure mission success while introducing new tools and capability for the space science community. These tasks engage the larger science and operational communities broadening the impact of the NASA GDC mission.

Heliophysics Mission Concept Studies
Abstracts of Selected Proposals
(NNH21ZDA001N-HMCS)

Below are the abstracts of proposals selected for funding for the Heliophysics Mission Concept Studies program. Principal Investigator (PI) name, institution, and proposal title are also included. 14 proposals were received in response to this opportunity. On September 23, 2021, 6 proposals were selected for funding.

Robert Allen/Johns Hopkins University
Heliospheric Distributed in-situ Constellation (HelioDISC)

Cross-scale and mesoscale dynamics are a fundamental science priority in space physics, but fall within an observational gap of current and planned missions. Particularly in the solar wind, measurements at the mesoscale (100 s RE to a few degrees heliographic longitude at 1 au) are crucial for understanding the connection between the corona and an observer anywhere within the heliosphere, as well as for revealing the currently unresolved physics regulating particle acceleration and transport, magnetic field topology, and the causes of variability in the composition and acceleration of solar wind plasma. Multi-point measurements with mesoscale separations are required to address this fundamental gap in our understanding, as studies using single-point observations do not allow for investigations into cross-scale and mesoscale solar wind dynamics and plasma variability, nor do they allow for the exploration of sub-structure of large-scale solar wind structures like the coronal mass ejections (CMEs), co-rotating/stream interaction regions (CIR/SIRs), and the heliospheric plasma sheet.

The Heliospheric Distributed In-Situ Constellation (HelioDISC) mission seeks to:
1) Determine the origin, variability, and cross-scale structure of the solar wind and transients
2) Determine the impacts of the 3D structure and sub-structure of the solar wind and transients on particle acceleration
3) Determine the effects of this cross-scale structure on suprathermal and energetic particle transport and propagation

To address these science goals, HelioDISC will employ the novel use of four identical spacecraft in Earth-trailing orbits near 1 au with varying drift speeds to span a range of mesoscale separations in the solar wind to achieve significant and innovative science return. The slightly different drift speeds allow the separation between the spacecraft to gradually increase over the lifetime of the mission, enabling investigations into multiple scales. Simultaneous, longitudinally-separated measurements of structures co-rotating over the spacecraft also allow for disambiguation of spatio-temporal variability, tracking of the evolution of solar wind structures, and determination of how the transport of energetic particles is impacted by these variabilities.

The payload of each HelioDISC spacecraft must measure the bulk solar wind plasma populations and magnetic field, as well as the suprathermal to energetic particle content, including composition. Hard X-ray measurements are also required to provide measurements of flare-related processes, release times, and connections to accelerated particles at 1 au. As such, the notional payload of each HelioDISC spacecraft consists of a vector magnetometer, ion composition and electron detectors spanning thermal to energetic ranges, and a hard X-ray telescope, with the inclusion of electric field instrumentation to be studied. Additional trade spaces include many elements of the mission architecture and operations (including orbital analysis, telemetry, and subsystems). Combining these multipoint observations, taken throughout/along large-scale structures, elucidates spatial sub-structure in the magnetic field and particle populations and effects of that variation on acceleration.

The HelioDISC mission concept study will use mission design facilities at the Johns Hopkins Applied Physics Laboratory Concurrent Engineering Laboratory (ACE Lab). The JHU/APL engineering team has experience with the dual lunar gravity assist orbits planned for HelioDISC, along with extensive experience operating heliospheric missions, including multi-spacecraft missions in the solar wind, and experience developing several of the notional payload instruments.

J**oseph Borovsky/Space Science Institute**
The Magnetosphere-Ionosphere Observatory (MIO)

The MIO mission concept is to operate a powerful 1-MeV electron accelerator on a main spacecraft in the equatorial nightside magnetosphere with the beam directed into the atmospheric loss cone to deposit ionizing electrons in the atmosphere sufficient to optically illuminate the magnetic footpoint of the spacecraft while 4 nearby daughter spacecraft make equatorial magnetospheric measurements. A network of ground-based imagers in Alaska and Western Canada will locate the optical beamspot thereby unambiguously establishing the connection between equatorial magnetospheric measurements and ionospheric phenomena. Critical gradient measurements will be made to discern magnetospheric generator mechanisms. This enables the magnetospheric drivers of various aurora, ionospheric phenomena, and field-aligned currents to be determined.

Science Goals and Objectives
The specific science goals of MIO are to determine: (1) What are the magnetospheric mechanisms that drive the specific types of aurora? (2) What magnetospheric processes drive critical ionospheric phenomena such as SAPS/SAID, STEVE, ionospheric irregularities, convection reversals, and the Harang discontinuity? (3) What are the magnetospheric counterparts of ionospheric boundaries and vice-versa? (4) What are the dominant magnetospheric gradients that drive field-aligned currents? (5) In the coupled magnetosphere-ionosphere convection pattern, who drives whom, when and where? The overarching objective of MIO is to unambiguously connect equatorial magnetospheric measurements to ionospheric phenomena. Specific objectives are to achieve the above 5

science goals and to support ground-based scientific campaigns and spacecraft-conjunction campaigns with the ionospheric, atmospheric, and magnetospheric communities.

Methods Proposed
Measurements in the magnetospheric equator are made on the main spacecraft carrying the electron accelerator and on 4 daughter spacecraft. The 4 daughter spacecraft make simultaneous radial and azimuthal gradient measurements in the equatorial magnetosphere that are critical to understand generator physics: gradients in ion and electron pressure, density, and temperature and gradients in flow (flow shear) and gradients in the magnetic field. Separate ion and electron flow velocities are required to identify generator processes that involve Hall currents.

Significance to the Solicitation and to NASA
Relevant to the ST Probes program, MIO addresses the fundamental physical processes of current driving in any astrophysical system and of coupling in a magnetospheric system. It addresses unsolved scientific questions about the physics of energy flow within the interconnected magnetosphere-ionosphere system. MIO focuses on our weakest link in the coupled system, which is the fact that we don t know what is coupled to what! MIO will conclusively fix that key knowledge gap throughout the complex, rapidly varying, nightside magnetosphere-ionosphere system. MIO will determine what forms of energy are converted in the magnetosphere to drive ionospheric phenomena, enabling us to better understand the impact on the magnetosphere of its driving of the ionosphere. Tests of the diverse theories of auroral generators can finally be made. And MIO will test ideas about who is driving whom in the coupled magnetosphere and ionosphere convection patterns. Suspected connections between the ionosphere and the magnetosphere can be definitely confirmed or refuted. Finally, by determining what nightside processes drive the diverse forms of aurora, MIO will provide the Rosetta Stone that will enable us to fulfill the longstanding desire to use auroral observations as a TV screen to monitor ongoing magnetospheric processes.

Via scientific campaigns with the magnetospheric, ionospheric, and atmospheric communities, and via scientist-in-the-loop control of accelerator firings, MIO will serve as a facility for Earth System Science.

George Clark/Johns Hopkins University
JUpiter s Global maGnetic Environment and RadiatioN ObservaTory (JUGGERNOT)

JUpiter s Global maGnetic Environment and RadiatioN ObservaTory, or JUGGERNOT, is a cross-disciplinary mission to Jupiter to push the frontiers of Heliophysics. The fundamental goal of JUGGERNOT is to explore the distinctive and universal processes operating around magnetized bodies. Building on experience and insights gained from the Van Allen Probes (formerly RBSP) mission, which revolutionized our understanding of Earth s radiation belts, JUGGERNOT will visit Jupiter, the most powerful natural particle accelerator in our solar system. To achieve this, we parse this goal into four science objectives:

1. Reveal the processes seeding Jupiter s uniquely intense radiation belts
2. Discover how Jupiter accelerates charged particles to such exceptionally high energies
3. Reveal the loss processes of relativistic charged particles in Jupiter s magnetosphere and resulting X-ray emissions
4. Discover how moon and ring materials in the Jovian space environment help create the radiation belts even though they simultaneously limit them

To address these objectives there are two aspects that drive JUGGERNOT s mission design. First, JUGGERNOT must perform several deep dives into the heart of the Jovian radiation belts with an equatorial (or very near equatorial) orbit that reaches inside 2 Jovian radii (RJ). Secondly, JUGGERNOT must deliver high-quality measurements of an intense and energetic radiation environment. The radiation environment of Jupiter poses difficult challenges that we expect to overcome based on preliminary dose estimates and APL s experience with the RBSP mission and planetary missions to Jupiter. Radiation effects will drive designs such as mass, power and instrumentation design and must be carefully understood. A baseline payload to address the proposed objectives may consist of the following instruments with associated scientific measurement requirements: 1) a particle instrument suite that can make energy and angle resolved measurements of suprathermal (10s of keV) to ultra-relativistic (>50 MeV) charged particles; 2) a plasma wave investigation capable of resolving various waves modes over a broad frequency (~1 Hz to 40 MHz) range; 3) a three-axis magnetometer; and 4) an imager capable of measuring soft (<2 keV) and hard (>2 keV) X-rays.

This concept proposes to use the proven APL Concurrent Engineering Laboratory (ACE Lab) procedure, where a team of engineers and scientists comes together in order to develop the mission details as well as their integration into the mission architecture.

JUGGERNOT is relevant to the Decadal Survey preparatory needs and the Solar Terrestrial Probes program and is therefore relevant to the HMCS scope. Specifically, this mission concept focuses on a cross-disciplinary science strategy to push the frontiers of Heliophysics to study other accessible planetary space environments (see finding 6.10 in Decadal Midterm Assessment). Furthermore, it is relevant to STP because it focuses on a long-term science strategy with an inter- and cross-disciplinary approach to address knowledge gaps that inhibit the advancement of the entire scientific field. Lastly, this concept fits into NASA s goal of including new and emerging topics that historically were not considered to be a part of the field, but where heliophysics expertise would enable significant scientific advances (see B.16-2 section 1.2). JUGGERNOT will expand our knowledge of radiation belt acceleration and processes in extreme magnetospheric systems, a truly Heliophysics science goal with broader impacts for both Planetary Science and Astrophysics.

Katherine Goodrich/West Virginia University
MULTI-POINT ASSESSMENT OF THE KINEMATICS OF SHOCKS (MAKOS)

The Multi-scale Assessment of the Kinematics of Shocks (MAKOS) mission is a concept that aims to take a bite out of one of the big, unanswered questions in collisionless shock physics. MAKOS has the overarching science goal to Understand the partitioning and conversion of energy at collisionless shocks under various conditions.
Collisionless shocks are a fundamental physical phenomenon with nearly universal cross-disciplinary relevance, affecting space plasmas from Earth s magnetosphere to astrophysical systems like stellar coronae, (exo)planetary magnetospheres, astrospheres, and supernovae. Shocks can play a crucial role in accelerating particles as energy is transferred between various particle populations and electromagnetic fields in such systems.
Though Earth s bow shock and interplanetary shocks in the solar wind have been studied for many years, our understanding of the key ion-kinetic-scale physical processes at play at these shock boundaries, remain poorly understood due to a lack of appropriate observations. Our understanding suffers due to gaps in the scales at which shocks have been probed, and inadequate comprehensive ion distributions. While many previous missions (e.g., ISEE, THEMIS, Cluster, Wind, & AMPTE) have provided both single- and multipoint measurements of shocks and made critical contributions to our understanding of shocks, none were outfitted with instrumentation, particularly particle and fields, specifically designed for shock studies nor were they able to probe ion-kinetic scales while also observing macroscales for context. Most recently, MMS has probed electron scales and underscored the importance of ion-scale structures. However, proper multi-point measurements at ion kinetic scales, where much of the relevant energy partitioning is thought to occur, are still missing.

To achieve its goal, MAKOS will focus on the following three science questions:
1) What is the partition of energy on either side of a collisionless shock?
2) What are the processes governing energy conversion at collisionless shocks?
3) How and why do these processes vary with shock orientation and driving conditions?

By investigating each of these questions, MAKOS will test and distinguish between several theoretical hypotheses suggested in the literature. For example, for question 2, MAKOS will determine the relative importance of proposed adiabatic and non-adiabatic energy conversion processes.
Investigating the detailed physics of collisionless shocks has direct relevance to the Solar Terrestrial Probe program, as well as to all four of the Heliophysics Decadal Key Science Goals (KSGs), specifically: understanding the extrema expected in the interplanetary space from interplanetary shocks (KSG1); understanding the nature of the boundary between Earth s magnetosphere and the solar wind, and the heliosphere and interstellar space (KSG2&3); and characterizing fundamental physical processes (KSG4). Likewise, MAKOS aligns with several objectives from the Heliophysics Roadmap (F2, F5, H1, and H4).

We will engage the design center at Southwest Research Institute (SwRI) to perform a concept study to bring MAKOS to fruition. To achieve its goal, MAKOS will require four observatories, each equipped with instruments specifically tailored to investigating shock dynamics. These include: low-energy particle composition velocity distribution functions at temporal resolution better than the proton gyroperiod (~5-10 s); 3D DC- and AC-coupled magnetic fields; at least 2D DC- and AC-coupled electric fields; and 4) energetic ion composition. MAKOS will use satellites in high-altitude, lunar-resonant orbits that maximize the annual number of bow shock crossings and solar wind dwell time, while systematically sampling a wide range of shock driving conditions. With at least three spacecraft, MAKOS can be configured to allow investigation of both ion-kinetic scale and simultaneous MHD scales context on both sides of the shock"

David Malaspina/University Of Colorado, Boulder
PILOT (Plasma Imaging LOcal and Tomographic experiment) Mission Concept Study

The Plasma Imaging LOcal and Tomographic experiment (PILOT) mission concept targets the fundamental physics of mass and energy transport in the terrestrial magnetosphere, using constellation observations to access an unprecedented range of spatial and temporal scales. Cold plasma originating in planetary ionospheres carries the bulk of mass and momentum within the magnetospheres of planets with atmospheres. PILOT traces the cold plasma populations (<1 eV   100 eV), which carry by far most of the system mass, and their dynamic regulation of magnetospheric sub-systems, as they exit the ionosphere, amass and energize in the inner magnetosphere, and redistribute to other regions. Terrestrial magnetospheric physics has a massive problem: knowledge of the fundamental processes that govern the exchange of mass and energy between the ionosphere, the inner magnetosphere, and the rest of the magnetosphere is severely limited. This limitation is the weakest link in our ability to treat the magnetosphere as a coupled system of systems . We propose to develop the PILOT mission concept, which targets the fundamental processes that govern mass, momentum, and energy transport through a planetary magnetosphere. The high-level PILOT science objectives are: [1] Identify and quantify the key processes that govern mass and energy exchange between the ionosphere and the magnetosphere, [2] Discover the pathways and processes governing cold plasma mass transport through and out of the inner magnetosphere, [3] Determine how, where, and when cold plasma mass acts most efficiently to regulate coupling between magnetospheric regions and between plasma populations. To accomplish these objectives, PILOT employs simultaneous in-situ (local), radio tomography (meso-scale), and imaging (global) measurements. Radio tomographic observations require a network of spacecraft to send and receive radio signals along lines of sight. Electron column density along these lines can be inverted to produce two-dimensional maps of total plasma density at high time resolution. Sampling the most dynamic cold plasma region requires spacecraft as string-of-pearls along two equatorial orbits (apogees ~4 and ~6 Re). Extreme ultraviolet imaging provides global contextual meridional observations, and in-situ observations provide ground-truth measurements. Only a few of the spacecraft need imaging and in-situ instruments. Most spacecraft are tomography-only, and therefore amenable to relatively inexpensive small sats. The minimum number of spacecraft required to meet PILOT objectives, their instrument configurations, concept of operations, and estimated cost will be determined during the concept study. Mission design facilities at the University of Colorado (CU), Laboratory for Atmospheric and Space Physics (LASP) will be used for the concept study. Key partners bring additional mission design (Advanced Space LLC) and instrument definition (SWRI) capabilities. The science study is supported by a diverse team of researchers from LASP, Boston U., SSI, SWRI, NASA Marshall, LANL, and UC Berkeley. LASP staff have demonstrated experience with studies of similar scale missions, most recently completing a NOAA Space Weather Architecture study, a Phase A study for an Astrophysics SMEX mission, producing two 2019 Discovery proposals, and performing technical development of the Emirates Mars Mission (EMM).

Nour Raouafi/Johns Hopkins University
4π Heliospheric Observing System

Science Goals and Objectives
The overarching goal of the 4π-HeliOS mission concept is to understand the global structure and dynamics of the Sun s convective zone, photosphere, corona and heliosphere, including the generation of solar magnetic fields, the origin of the solar cycle, and the causes of solar activity. To address this goal, the proposed concept focuses on the four fundamental science questions: (1) What are the characteristics of the flows and magnetic fields at and below the photosphere, particularly in the unexplored polar regions, and how do they drive the global dynamo to create sunspot activity over the solar cycle?; (2) How does the magnetic energy flow through the different layers of the solar atmosphere and accumulate in the corona?; (3) How are non-potential fields created in the corona, how do they store energy and evolve towards eruption, and what is the role of the large-scale magnetic field?; and (4) How do conditions in the solar wind vary with latitude and longitude in response to changing global solar conditions?

Mission Concept Description
The primary mission requirement for 4π-HeliOS is to achieve complete coverage of the solar sphere for >80% of the mission lifetime. The strawman payload consists of two pairs of spacecraft, each carrying a remote-sensing and in situ payload. The first pair, referred to as 4π -out uses Jupiter gravity assists to reach a highly inclined orbit (>60° relative to the ecliptic) near 1 AU (TBS). The 4π -out spacecraft use ion engines to circularize their orbits and increase their relative phasing by 180°. The second pair, referred to as 4π -in , is launched into elliptical Trojan orbits around the Sun-Earth L4 and L5 Lagrange points, via lunar and terrestrial gravity assists (TBS). The 4π -in spacecraft oscillate between 40° and 90° relative to the Sun-Earth line during the year, while the 4π -out spacecraft orbital planes rotate with respect to the Earth-Sun line and L4/L5 points over the course of a year. The combined observations of the four spacecraft provide nearly continuous global coverage of the photospheric magnetic field, the solar corona, and local heliospheric conditions, while enabling both global and local helioseismology measurements throughout the solar convective zone.

Driving Science Requirements

Question 1 requires continuous surface and subsurface velocity, and surface magnetic measurements from multiple vantage points, particularly of the solar poles for at least 3 consecutive rotations above 60° latitude at a time. This drives the minimum inclination and orbital period of the 4π -out pair.
Question 2 requires uninterrupted coverage of active-region lifecycles. This requirement drives the orbital design of the 4π -in pair as well as the need for additional observations out of the ecliptic.
Question 3 requires accurate 3D reconstructions of coronal structures from about 1.1 to 15 solar radii, necessitating an uninterrupted EUV FOV out to 3 Rsun and white-light 1.5-15 Rsun. This drives the minimum angular separation among the four members of the 4Π constellations to be at last 45°.
Question 4 requires continuous measurement of the in-situ plasma parameters and drives the requirement for 4π coverage.
The mission design presumes that similar measurements will be available from the Earth vicinity.

Mission Design Facilities
The mission design will take place at the Johns Hopkins Applied Physics Laboratory Concurrent Engineering Laboratory (ACE Lab), which is a premier mission design center, fostering rapid and collaborative mission design evolutions. The ACE Laboratory provides a full suite of tools and an extensive library of previous missions and concept documentation. Mission (trajectory) design is a critical APL capability, often becoming an enabling factor with respect to achieving mission goals and objectives within cost and schedule constraints.

Interdisciplinary Science for Eclipse Program
Abstracts of Selected Proposals
(NNH21ZDA001N-ISE)

Below are the abstracts of proposals selected for funding for the Interdisciplinary Science for Eclipse Program (ISE) Program. Principal Investigator (PI) name, institution, and proposal title are also included. Twelve (12) proposals were received in response to this opportunity. On July 13, 2021, six (6) proposals were selected for funding.

Xinzhao Chu/University Of Colorado, Boulder
Observations of 2021 Antarctic Solar Eclipse from McMurdo Station for Study of the Ionosphere-Thermosphere-Mesosphere Coupling

The 4 December 2021 solar eclipse will be visible only from Antarctica and the Southern Ocean. Therefore, this eclipse will be logistically challenging to observe. We propose a unique study to observe the solar eclipse and its impacts on the meteoric metal layers in the ionosphere, thermosphere, and mesosphere (ITM) with two sophisticated Na Doppler and Fe Boltzmann lidars that have been installed and running at McMurdo Station (77.84ºS, 166.67ºE) in Antarctica. These, along with numerical simulations of the metal layers, satellite observations, and other ionospheric and magnetospheric measurements, make this solar eclipse a unique opportunity to advance the understanding of ITM coupling and meteoric metal sciences.

Permanent neutral metal layers of Fe and Na species in the upper atmosphere (~80-110 km) originate from meteoric ablation and sputtering. Thermosphere-ionosphere metal (TIMt) neutral layers above the permanent metal layers, in the altitude range from ~110 to 200 km, were discovered only 10 years ago in Antarctica and are produced from the neutralization of metal ions. These metal layers provide unique tracers for studying the solar-space-atmosphere interactions during the Dec 2021 solar eclipse event. This proposal is focused on addressing the overarching science question, Does the solar eclipse produce statistically significant variations in the Fe and Na metal layers and impact the plasma-neutral coupling in the ITM system? We will combine multi-instrument observations from McMurdo, Antarctica with numerical simulations to investigate the presence/absence of three potential impacts of the solar eclipse: 1) Solar effects on the bottom sides of Fe and Na layers that have different responses to photochemistry, 2) TIMt layer changes caused by the solar-eclipse-induced sudden and large changes in the electron and ion concentrations and plasma drift via plasma-neutral coupling, and 3) variations in the permanent Fe/Na layers and temperatures due to the changes of gravity waves induced by the supersonic motion of the Moon s shadow. Our primary datasets are data from two resonance-fluorescence lidars at McMurdo, SuperDARN, ionosonde, magnetometer, and output from WACCM-X simulations supplemented with satellite measurements of atmospheric minor species, solar winds, etc.

By comparing the observations and simulations surrounding the Dec 4 2021 solar eclipse event with 10-years of observations at McMurdo, the proposed study will provide critical new information about the photochemistry and plasma-neutral coupling in the D and E regions of the Antarctic ionosphere. We will take a novel and interdisciplinary approach for this research by using the metal layers as unique tracers. The proposed research will integrate historical lidar data, lidar data captured during the 2021 eclipse, and various other ionosphere-magnetosphere measurements to study chemistry, neutral dynamics, and electrodynamics in the mesosphere and lower thermosphere. This is a step forward towards a grand understanding of meteoric metal layers and how they provide a unique way of exploring the connection between the Sun and Earth s atmosphere, as well as the coupling in the ITM system.

Our science objectives are highly relevant to the NASA eclipse science and to the high-level Heliophysics decadal survey goals, Determine the dynamics and coupling of Earth s magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs , and Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe . The proposed study will use the eclipse as a point-response function of solar energy input to verify several important and interdisciplinary ideas regarding the photochemistry of metal species, ITM coupling, and their response to the solar and terrestrial inputs. It helps address the Heliophysics objective of understanding atmosphere-ionosphere coupling.

Shadia Habbal/University of Hawaii, Honolulu

Quantifying the plasma properties of the coronal sources of different solar wind streams with multi-wavelength observations during the 2021 December 4 total solar eclipse

Science Goals and Objectives: Total solar eclipses provide unique opportunities to explore the inner corona in an uninterrupted heliocentric distance of 1 to 5 solar radii (Rs), with an angular resolution of 1- 4 . Through multiwavelength imaging and spectroscopy, capitalizing on the outstanding diagnostic capabilities of coronal emission lines in the 350 to 1100 nm range, the basic parameters of coronal species, namely their density, electronic and ionic temperature, relative ionic abundance, outflows through Doppler shifts, as well as magnetic field topology, can be inferred over a radial span where their most pronounced evolution occurs. Not only do these parameters dictate the evolution of distinct solar wind streams starting from their sources, but are critical for space weather forecasting, and for guiding models and their validation. Total solar eclipse observations thus yield key plasma parameters in the spatial gap of existing instrumentation on ground- and space-based platforms. The goal of this proposal is to capitalize on the proven diagnostic capabilities of white light and ionic emission to

characterize the plasma properties of the sources of quiescent and dynamic solar wind streams during the 2021 December 4 total solar eclipse. The objectives are to (1) link the inner corona to in situ measurements of the solar wind to be acquired by the Parker Solar Probe (PSP) and Solar Orbiter (SolO) during their close approaches to the Sun, coupled with model studies, (2) provide precursor coronal insight for the geographically optimal 2024 total solar eclipse, (3) test seaborne equipment for eclipse observations, and (4) provide eclipse science to the widest audience possible.
Methodology: The seaborne multi-wavelength imaging and spectroscopic observations of the 2021 December 4 total solar eclipse over Antarctica will be achieved by operating our proven heritage instrumentation with stabilizing platforms, such as gimbals and hexapods, together with proven image alignment and processing tools. To infer the plasma parameters of the inner corona, the instrumentation consists of: (1) White light imagers of the inner corona yielding an angular resolution of 1 < 1.5 Rs, and 5 up to 10 Rs. (2) Multi-wavelength imaging with three pairs of identical scientific-grade CMOS cameras outfitted with 300 mm lenses, and narrow (0.5 nm) band-pass filters centered on Fe X (637.4 nm), Fe XI (789.2 nm) and Fe XIV (530.3 nm). For each pair, one element is centered on the line, while the other is centered on the neighboring continuum, shifted by 1.0 to 3.0 nm from the line-center. Operated simultaneously, subtraction of the continuum for each line pair then yields the coronal line emission. (3) Two partially-multiplexed imaging spectrometers acquiring the rich coronal spectrum over a 4 Rs slit-length in the N-S direction, with a wavelength range of 350 to 1100 nm at each pixel along the slit. The dual channel spectrometer covers the 550 640 nm and 660 1100 nm wavelength ranges, while the UV spectrometer covers 350 to 550 nm. The motion of the slit during the ~ 2 mins of totality will yield spectra over an area of ~ 4Rs x2Rs off the limb. With a spectral resolution < 0.03 nm, Doppler shifts and Doppler broadenings of 20 km/s and ~ 0.3 MK respectively, can be measured with both spectrometers. The link between these data products and in situ observations from PSP and SolO will be verified by forward modeling the identified coronal sources using fluid and kinetic plasma simulations.
Relevance to Heliophysics: The proposed eclipse observations address NASA s Heliophysics goal to understand the Sun and its interactions with the Earth and the Solar System, including space weather , and objectives to: Explore and characterize the physical processes in the space environment from the Sun to the heliopause and throughout the Universe. It will also support Investigations of the origin and behavior of the solar wind and transient structures.

Sebastijan Mrak/Boston University
The impacts of abrupt changes in photoionization on high-latitude electrodynamics

The high-latitude ionosphere is electromagnetically coupled with the magnetosphere, allowing magnetospheric currents to close, while the ionospheric conductivity controls how the currents are closed and how much energy is dissipated. One of the primary sources of the high-latitude plasma   hence conductance   is solar photoionization. A solar eclipse is a natural event that could be utilized as a laboratory experiment for studying how changing ionospheric conductivity impacts high-latitude electrodynamics and the resulting interhemispheric asymmetries. In particular, we will study the effects of abrupt spatiotemporal changes in the solar X-ray and Extreme Ultra Violet (XUV) irradiance within a penumbra. These transition regions of steep XUV changes are a projection of solar active regions on the Earth s atmosphere. The XUV energy deposition peaks in the E-region where the dissociative recombination of nitride oxide and molecular oxygen has characteristic lifetimes in the order of minutes. Thereby, the conductivity, which peaks in the E-region, changes rapidly following the trend of the XUV irradiance. The 4 December 2021 eclipse is unique in the sense it covers the whole southern polar region, so it provides an opportunity to investigate how high-latitude electrodynamics is affected by a large-scale XUV reduction and sudden XUV gradients. During the 2017 total solar eclipse, we have shown that the XUV transition regions had cross-sections in the order of 500 kilometers, where the XUV irradiance changes by 10-20%. The effects of these transition regions were measured by Global Navigation Satellite Systems (GNSS) and Defense Meteorological Satellite Program (DMSP).

The proposed research will utilize modeling frameworks, whose results will be compared against the ground- and space-based observations of plasma parameters, derived ionospheric conductivity, particle precipitation, and field-aligned currents. We will focus our efforts on one specific scientific objective: What are the impacts of steep changes in EUV irradiance on high-latitude electrodynamics and particle precipitation, and what are the resulting conjugate effects.

We will compute the eclipse occultation mask utilizing XUV images taken by Solar Dynamics Observatory (SDO) Atmospheric Imaging Assembly (AIA). The resulting eclipse occultation factors are computed as a function of geographic latitude, longitude, altitude. We will model the ionosphere-thermosphere (IT) response to the eclipse using Global Ionosphere Thermosphere Model (GITM). GITM will provide a critical diagnostic tool to determine the effects of the steep XUV changes on the IT system. GITM will provide three solutions: (1) Baseline run without any modification, (2) response to an idealized eclipse, (3) response to the eclipse using the 4D SDO-XUV mask. By comparing the three results, we will isolate contributions of the transition XUV regions.

We will compare the modeling results with ground-based Total Electron Content derived from GNSS networks in Antarctica and Northern America and in-situ satellite observations. Conjugate effects will be studied with Millstone Hill Incoherent Scatter Radar at mid-latitudes, while All-Sky Cameras will provide proxies for precipitation and conductivities. In-situ measurements using DMSP and POES will be used to measure particle precipitation, while DMSP and Swarm constellations will be used to measure plasma parameters, derived field-aligned currents, and neutral density.

This proposed study will evaluate fundamental plasma density structures in the ionosphere, thus addresses LWS program objective #1 "Understand solar variability and its effects on the space and Earth environments with an ultimate goal of a reliable predictive capability of solar variability and response", and Decadal Survey goals #2

"Determine the dynamics and coupling of Earth s magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs".

Gareth Perry/New Jersey Institute Of Technology

An e-POP investigation of the ionosphere-thermosphere system's regional response to the December 4, 2021 solar eclipse

The December 4, 2021 total solar eclipse presents a unique opportunity to measure and assess the response characteristics of the Earth s coupled ionosphere-thermosphere (IT) system to an impulse-like event. The trajectory of the eclipse s umbra and penumbra, and the state of the COVID-19 pandemic make this eclipse particularly difficult for deploying and operating ground-based sensors to assess the IT system s response to the event. To overcome these challenges, we propose to use the Enhanced Polar Outflow Probe (e-POP) payload onboard the Cascade Smallsat and Ionospheric Polar Explorer (CASSIOPE) spacecraft to carry-out a one-month long campaign to investigate the IT system s regional response to the eclipse from low-Earth orbit.

CASSIOPE (hereafter referred to as e-POP) is a spacecraft with a high-inclination orbit. Current orbit projections show that e-POP will intersect the eclipse s path of totality within 30 minutes of totality on December 4, 2021, at 888 km altitude. We will use two of e-POP s instruments, the Radio Receiver Instrument (RRI) and the Global Position System receiver-based Attitude, Position, and profiling experiment   Occultation (GAP-O) instrument to investigate two signatures of the IT system s response to the eclipse. First, we will search for signatures of travelling ionospheric disturbances (TIDs) in the eclipse region. Eclipse induced TIDs is a hypothesized IT system response which lacks decisive observational evidence confirming the connection. The second IT system response signature is the transformation of the region s vertical plasma density profile during the eclipse, from depletion to recovery. The proposed investigation will examine these two distinct IT system responses using two distinct instruments and techniques and modeling   an interdisciplinary science investigation for the eclipse.

The proposed team, led by PI Perry, has extensive experience planning and executing interdisciplinary observation campaigns with e-POP, including several solar eclipses, with a proven track record of high impact scientific results. The team members are well versed in solar-ionosphere-thermosphere coupling physics, possess an intimate knowledge of e-POP and its capabilities, and have strong connections with the e-POP operations team and international science community, ensuring that the proposed research will be carried-out successfully.

Kevin Pham/University Corporation For Atmospheric Research (UCAR)
Impact of Eclipse on the Magnetosphere through Magnetosphere-Ionosphere-Thermosphere Coupling

BACKGROUND/MOTIVATION:
Impact of solar eclipses on the state and evolution of the magnetosphere has not been extensively studied. However, recent works using a coupled magnetosphere-ionosphere-thermosphere model demonstrated that solar flares, which were never considered in the context of the magnetosphere, appreciably disturb the structure of the dayside magnetosphere. The solar flare caused field-aligned currents to increase in peak intensity and moved the magnetopause earthward in response. Therefore, we believe that it is worth investigating to what extent the global scale effects of eclipses on the thermosphere-ionosphere system lead to changes in the magnetosphere. The main difference being that solar flares introduce a sudden global step-function change in the conductance, while eclipse-induced changes are more progressive in time and the shadow appears in one hemisphere. The 4 December 2021 total solar eclipse occurs at high latitude where magnetosphere-ionosphere coupling is most pronounced. This eclipse also occurs in the southern hemispheric summer and near solstice when the southern hemisphere is more sunlit. These conditions provide an ideal path of totality for the eclipse to influence the geospace environment.

SCIENCE OBJECTIVES:
This study aims, for the first time, to utilize global simulations to identify and characterize the potential impacts of the eclipse on the magnetosphere. The results will provide guidance for further observational investigations to confirm the model predictions. The study addresses the following three specific science questions:
1) How do changes in the electrodynamics of the system due to the solar eclipse affect the geospace coupling?
2) How does the size of the magnetosphere, as defined by magnetopause and bow shock location, change in response?
3) How do interhemispheric asymmetries of the system change in response to the eclipse shadow in the southern hemisphere?

METHODOLOGY:
We will employ the fully coupled magnetosphere-ionosphere-thermosphere geospace model, the Multiscale Atmosphere Geospace Environment (MAGE) model, to simulate the consequence of the 4 December, 2021 eclipse on the geospace environment with an emphasis on the magnetosphere. Prior to 4 December, 2021, we simulate the eclipse using typical solar wind and solar irradiance for a moderate CME and CIR storm under solar minimum conditions. Multiple simulations will be done in which the eclipse occurs at differing times; prior to, during, and after the main phase of the storms. This provides a comprehensive analysis of how the eclipse influences the geospace system. As an observational challenge, results will be made available to the research community to aid in identifying observational priorities, especially in the magnetosphere. Virtual satellites corresponding to projected positions of THEMIS, MMS, Geotail, and GOES spacecrafts will fly through these simulations. For global coverage, AMPERE and GPS derived TEC

will be examined. Comparison of predicted measurements will determine the expected signatures of the eclipse. After 4 December 2021, we simulate the geospace environment twice using the MAGE model. The first simulation uses the observed solar wind conditions and the eclipse path. The second will be conducted with observed solar wind conditions without the eclipse. Comparisons of the two simulations will isolate the impacts driven by the solar eclipse effects.

RELEVANCE:
The proposed work is directly relevant to the goals of the NASA Heliophysics Decadal Survey to Determine the dynamics and coupling of Earth s magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs. The study uses the latest fully coupled geospace model to examine how the eclipse effects propagate into and influence the magnetosphere from the ionosphere and thermosphere. The study also provides the context for the widely dispersed, multi-instrument measurements in geospace.

Shun-Rong Zhang/Massachusetts Institute of Technology
2021 Antarctic Solar Eclipse: Ionospheric response in the southern and northern hemispheres

The Sun provides the ultimate energy input to geospace in several forms including solar radiation. A sudden reduction in EUV flux during a solar eclipse results in sharp decreases of both photoabsorption by neutral constituents and ionospheric photoionization. Supported by the 2017 NASA ISE program and other agencies' programs, we conducted a series of eclipse studies resulting in 10+ peer-reviewed papers. Highlights include observations of eclipse-induced bow-shaped ionospheric waves, dynamic and photochemical changes in the midlatitude ionosphere over Millstone Hill (MH), conjugate effects, and studies of three recent eclipses in 2019 and 2020.

The December 2021 Antarctic eclipse will provide a very unique geographic configuration with great potentials for community understanding of ionosphere-thermosphere-plasmasphere (I-T-P) coupling during a sudden reduction in solar irradiation. The Moon's shadow path will sweep through the area containing the well-known Weddell Sea ionospheric anomaly (WSA), where diurnal maximum electron density in December (southern summer) occurs not during the day but at night even though the Sun remains above the horizon. This will provide an unprecedented opportunity to revisit a classical ionospheric mystery in the Antarctic.

The Moon's shadow will pass near Palmer on the Antarctic Peninsula, magnetically conjugate to the MH incoherent scatter radar (ISR) site near Boston. Previous MH observations have noted a predawn wintertime electron temperature (Te) enhancement, explained in terms of impact from conjugate photoelectrons originating near Palmer. The 2021 Antarctic eclipse will allow us to examine the predawn conjugate photoelectron impact, as eclipse modulations in photoelectron production due to the Moon's shadow rapidly turn the Antarctic photoelectron source on and off.

We propose to use this extremely rare observation opportunity to investigate two I-T-P coupling questions: [Q1] What are the magnetically conjugate effects of the Antarctic eclipse? In particular, [Q1.1] are there any changes in conjugate predawn Te, Langmuir mode visibility from photoelectron flux changes, and 630 nm redline brightness? [Q1.2] Are there any conjugate TEC variations? [Q2] What is the solar eclipse impact on the WSA? Can observations of eclipse ionospheric responses help understand WSA candidate driving mechanisms: zonal and meridional winds (perturbed also by the Moon's shadow) and photoionization?

We will analyze multiple observational datasets, including [1] MH ISR ionospheric altitude profiles and Langmuir mode ("plasma-line") F2 peak brightness; [2] MH FPI relative brightness; [3] GNSS TEC observations in the Antarctic region and its conjugate region; and [4] GOLD daytime O/N2 observations. A 5-day MH ISR campaign centering on the eclipse day will be conducted. These data [1-2] will be combined with historical data near sunrise to explore (Q1.1) conjugate photoelectron impact as manifested in Te, Langmuir mode brightness, and redline brightness. Data [3] will be also used to examine conjugate TEC variations (Q1.2). Data [3] will be further used for eclipse effects on WSA regional TEC (Q2). Data [4] from GOLD, related to Q2, will be used to understand neutral composition response to the eclipse and its contribution to the WSA.

This proposal directly addresses ISE 2021 program goals of connecting eclipse effects to ITM system studies, as WSA and conjugate photoelectron impacts remain active ionospheric research topics in the Heliophysics community. It addresses a key Heliophysics research objective to explore and characterize physical processes in the space environment from the Sun to the heliopause and throughout the universe.

Living With A Star Tools and Methods
Abstracts of Selected Proposals
(NNH21ZDA001N-LWSTM)

Below are the abstracts of proposals selected for funding for the Living With a Star Tools and Methods program. Principal Investigator (PI) name, institution, and proposal title are also included. Thirty-nine proposals were received in response to this opportunity. On January 26, 2022, twelve proposals were selected for funding.

Alex Antunes/Johns Hopkins University
Readying 25 years of full-disk EUV images for machine learning

We will create the full set of ML-ready EUV data from 1995 to present, accessible via the cloud, by bringing in historical restoration of the STEREO/SOHO era in with present datasets into an machine-learning (ML)-ready dataset. The data synthesis will enable 360 degree views of sun and the combined cadences will allow better use of less-sampled EUV instruments with higher-cadence sets. Use of cloud computing will simplify researcher access compared with current high-level datasets. Solving this requires creating homogenous data from source instruments of different resolution, cadence, and slight wavelength differences as well as dealing with cross-calibration. While spatial sampling is a solved problem, differences in cadence in particular will require experimentation to yield cross-comparable results. This work enables research on events, evolution of solar irradiance, segmentation approaches, 360 degree maps of the sun, and other research topics as well as for use with space weather. In terms of data access, at APL we have access to the STEREO/EUVI and SOHO/EIT data, while SDO has created ML-ready data (Galvez et al, 2019). Our team already works with ML and cloud heliophysics data as well as the open standard Heliophysics API (HAPI 2.0) and SunPy.

Graham Barnes/NorthWest Research Associates, Inc
Faster, Better, Deeper: Utilizing Deep Learning to Produce Enhanced Near Real Time Inversions from HMI Data for Space-Weather Modeling.

We propose to use a machine learning (ML) algorithm to simultaneously improve the quality and significantly speed up the production of near real time (NRT) vector magnetic field data from the Helioseismic and Magnetic Imager (HMI) on board the Solar Dynamics Observatory. Our general approach will be to use convolutional neural networks (CNN), based on a U-net architecture, combined with regression-by-classification, with Stokes vectors as the input for the network, and various outputs from a Milne-Eddington inversion as the targets that the networks will be trained to produce. This approach has already been trained and validated to provide high fidelity reproductions of the present science quality inversion products of the HMI pipeline at their original resolution (Higgins et al 2021b), as well as to emulate the results of the pipeline inversions of Hinode SOT-SP data (Higgins et al 2021a).

The same type of network will be trained on the NRT Stokes spectra from HMI with SOT-SP inversions as the target. The results will enhance the present NRT HMI pipeline data product by (1) providing the magnetic field estimate for every pixel, including polar regions, (2) reducing systematic bias in the field inclination through an independent estimation of the magnetic fill factor, and (3) estimating the full physical magnetic field vector, i.e., the physically meaningful quantity used as the boundary condition for many space weather models, effectively through an ML-based resolution of the inherent 180 degree ambiguity.

These enhanced data products, produced with substantially reduced processing time, may be useful in space weather forecasting, particularly the real time modeling of eruptions that produce energetic particles, thus giving additional warning for impact on spacecraft throughout the heliosphere. This benefit addresses the third Living With a Star objective, "Human Exploration and Development: LWS provides data and scientific understanding required for advanced warning of energetic particle events that affect the safety of humans." As an additional product, the machine learning-ready data set used to train the network will be provided to the community, ready for similar or hopefully ground-breaking efforts in ML research to improve the inversion and interpretation of Stokes spectropolarimetric spectra.

The CNN to produce near-real-time full-disk vector-field data series will be implemented to run at Stanford University within 18 months of start date, with the output available through the Joint Science Operations Center, the standard repository for HMI and other NASA-mission data. Also within 18 months, the ML-ready SDO-Hinode dataset and corresponding evaluation code will be archived at the University of Michigan Library Deep Blue data repository. This system provides a DOI for the published data, and access via both browser and Globus (which facilitates inter-institutional transfers).

John Dorelli/NASA Goddard Space Flight Center
Vlasov Informed Super Resolution (VISR): A Deep Learning Approach for De-Aliasing Particle Data

Earth's magnetosphere is a complex system with plasma dynamics occurring on a vast range of spatial and temporal scales. Understanding how kinetic plasma dissipation processes shape the large scale structure and dynamics of the magnetosphere remains one of the great challenges of heliophysics. The community's effort to develop the next generation of predictively powerful global space weather models would benefit greatly from observations of plasma dissipation processes on millisecond time scales. NASA's Magnetospheric Multiscale (MMS) mission has paved the way for such observations, but important processes like turbulent dissipation and wave-particle interactions remain marginally resolved at best due to particle instrument aliasing.

We propose to develop a new tool for the heliophysics community -- Vlasov Informed Super Resolution (VISR) -- that uses deep learning to combine time-aliased particle data with the Vlasov equation to recover physically meaningful information below the energy sweep time scale. VISR will make use of Physics Informed Neural Networks (PINN), a recent development in deep learning that has shown promise for a wide range of applications. We will apply VISR to data collected by the Fast Plasma Investigation (FPI) on MMS. After prototyping and validating VISR on test data generated by analytic solutions of the Vlasov equation, we will scale up to production on the ADAPT GPU cluster at NASA-GSFC.

VISR will be made available to MMS team members at the MMS Science Data Center (SDC) no later than 18 months after the start date of the project. After an additional 6 month beta testing period, VISR will be made publicly available under an open source license at both the MMS SDC and an open github repository.

Kiran Jain/ National Solar Observatory
Application of Machine Learning to Improve the Detection of Active Regions in the Sun's Far Hemisphere

Scope and Goal: The measurement of magnetic activity on the solar surface has multiple applications, especially in space weather forecasting. The near-side regions of high magnetic concentration (known as active regions) can be directly observed while for the far-side regions, at present, we mostly rely on indirect methods based on the technique of local helioseismology. In this technique, we map the phase shift (travel time delay) between acoustic waves traveling into a region and its echo. This technique is being used for last two decades and shows/indicates the presence of active regions on the backside of the Sun. However, the detection of the active regions so far is mostly limited to big regions, though there are numerous examples of smaller active regions producing severe space weather events. In the proposed work, we plan to improve the detection of solar active regions on the far-side of the Sun by developing a Machine Learning (ML) tool for application to the helioseismic phase-shift maps. The goal is to lower the threshold of the required strength of the seismic signal for detecting active regions of different sizes. This will be done by reducing the noise and enhancing the seismic signal in farside phase-shift maps.

Methodology and Data: The proposed work is based on the following steps:

(1) Compile a database of GONG helioseismic maps of the Sun's far hemisphere from archives available at the National Solar Observatory (https://nso.edu/data/nisp-data/) concurrent with periods during which NASA STEREO had full EUV coverage of the same. (NSO/GONG has been posting twice-daily synoptic helioseismic maps of the

Sun's far hemisphere at this website since 2006 from 24-hr time series of Dopplergrams. These are archived as open-source datasets (https://farside.nso.edu) and can be easily accessed through the internet.)

(2) Design and train ML-based parameterized algorithms that, applied to the helioseismic phase-shift maps and STEREO-EUV images, propose to recognize and characterize the signatures of active regions.

(3) Formulate an analogous system for validation of the algorithm for application to the helioseismic maps based upon the agreement of its identifications and characterizations derived from the STEREO EUV maps.

(4) Determine the parameter set of the algorithm that optimizes the validation formulated in (3).

(5) Implement the algorithm in the existing pipeline for improved detection of active regions on the farside.

Relevance: The proposed work is directly relevant to one of the NASA's Living With A Star objectives, i.e., ``to quantify the physics, dynamics, and behavior of the sun-Earth system over the 11-year solar cycle'' and contributes significantly to advances in operational space weather forecasting. Our work will improve the use of heliophysics data to immediately benefit users of science data and will enhance the overall experience of the users of science data.

The Archive: We plan to deliver the Machine Learning Trained Active Region Recognition Algorithms (MLTARRA) tool developed in this work and a detailed README file to NASA's Community Coordinate Modeling Center (CCMC) within three months of the completion of this project. The near-real-time forecast and the related data products will be posted at the National Solar Observatory's website (www.nso.edu).

Jeremiah Johnson/University of New Hampshire, Durham
Producing Homogeneous, Machine-Learning Ready Auroral Image Databases Using Unsupervised Learning

Dynamic interactions between solar wind and magnetosphere gives rise to dramatic auroral forms that have been instrumental in the ground-based study of magnetospheric dynamics. Although the general mechanism of aurora types and their large--scale patterns are well-known (Newell et. al. 2009), the morphology of small- to meso-scale auroral forms observed in all-sky imagers and their relation to the magnetospheric dynamics are still in question. A better understanding of the morphology of auroral forms is critical to our understanding of magnetospheric dynamics and the coupling of the magnetosphere to the upper atmosphere. Machine learning offers the possibility of surfacing new knowledge in this area, but most existing auroral image databases are not yet machine learning-ready. A key issue is the lack of ground-truth labels: most widely-used machine learning algorithms are supervised, and without ground-truth labels, cannot be used.

The scientific goal of this project is to deliver a large-scale, homogeneous, machine learning-ready database of auroral images that will enable machine learning-driven investigations into the morphology of auroral forms and the corresponding relationship between these forms and magnetospheric dynamics.

To achieve this goal, we will develop a state-of-the-art unsupervised machine learning algorithm capable of automatically labeling 16 years of white light auroral image data from Time History of Events and Macroscale Interactions during Substorms (THEMIS) ground-based All-Sky Imager (ASI) array. Our approach avoids the necessity of ground-truth labels during training by learning latent representations of the input data that capture inherent structural relationships. These representations can then be used for downstream tasks such as automatic labeling and cluster analysis or investigated in their own right. This work will produce the largest publicly-available, labeled, homogeneous, machine-learning ready auroral image database created to date. It will enable the space science community to conduct statistical studies on the relationship between different categories of auroral images, near-earth solar wind conditions, and geomagnetic disturbances at the earth's surface that were not previously possible. It is relevant to the high-level goal to "Determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial input" from the Heliophysics Decadal Survey. The machine learning-ready dataset produced by this research, along with the models and software necessary to reproduce the results, will be delivered to the Space Physics Data Facility on or before the conclusion of the project on October 31, 2023.

Michael Kirk/Atmospheric & Space Technology Research Associates
Discovering Micro Events in AIA using Machine Learning

The catalogue of SDO AIA EUV images is now more than 6 PB and growing every day. Each of these images has 16 million pixels and the database is over 151 million images. Can we search the 2.5 quadrillion pixels to find single pixel eruptions? Does AIA regularly detect coronal 'campfires,' seen by Solar Orbiter? What other small dynamic phenomena are prevalent in the corona?

It is impossible to use conventional methods to analyze such an immense amount of data. This proposal utilizes the cosmic ray spikes database (so-called AIA spikes) and unsupervised machine learning (ML) techniques to search for single pixel eruptions. The cosmic ray spike removal image-cleaning algorithm runs automatically on the level-0 AIA images and removes isolated bright points which are usually cosmic rays but occasionally captures some small bright coronal features. Through using the spikes catalogue, we reduce our data science problem by over three orders of magnitude from a total AIA archive of 1015 pixels to 1012 pixels   still a very large data science problem. Through reposing our science question into a data science framework, we further reduce the scope of the parameter space. Previous research has identified that different types of solar eruptions have a distinct evolution when observed in each of the 7 different AIA EUV passbands. For example, a coronal jet regularly has a different peak intensity than a solar flare in the 131 and 171 channels. Thus, passband intensity abstracts events into a 7-dimenstional space where each dimension represents the intensity in an EUV channel.

A recent publication by Young et al. (2021), explores the relationships between the physical properties of AIA spikes in the 171 channel and their coronal environments in 126 cases. They found that 96% of the physical features identified in the AIA spikes have a diameter of less than 2 arcsec, can occur anywhere on the solar disk, and typically evolve over a period of less than 5 minutes, demonstrating that spikes are compact in both time and space. Combining the two spatial and one temporal coordinates with the 7-EUV channel coordinates yields a 10-dimensional space defining a spike.

This work will further develop temporal and spatial filters for linking spikes to their physical origin. Spatial-temporal intersections between spikes in different wavelengths give us insight into how these small features are linked together. Over a two-day sample set, we observe that about 6.5% of the remaining physically interesting spikes occur in all 7 AIA filters. Mapping these spikes back onto the coordinates of the solar surface, there is a concentration in the same location as larger solar features such as coronal holes and active regions. Where individual spikes are coincident in time and location between different AIA wavelengths in this sample set will further refine our physical filters. We eliminated over 99% of the spikes which are genuine cosmic rays using this technique in a two-day demonstration period in 2011.

Methodology and Data

This effort will build a database of every AIA spike in 10-dimensional space (EUV wavelength plus space and time). Abstracting the spikes from its physical origin will allows us to use unsupervised ML to further investigate trends and segment our dataset of over 1010 detections. Utilizing an innovative mix of Bayesian and clustering methods, we will identify clusters of spikes and label commonalities between groups of detections. Once this labeling is complete, we can return to our science question and ask if a group is in fact a 'campfire' observation or some other coronal eruption through extracting a subset of individual spikes, embedding them into a context region, and matching the identified label to the clusters in the database - a process described in Young et al. (2021). This effort delivers a high-value database of AIA spikes that have a coronal origin with labels of likely physical phenomena they represent.

Bennett Maruca/University Of Delaware
Large-Scale Average Trends in Plasma Parameters Across the Heliosphere

Goals and Objectives. The goal of this project is to compile and synthesize historical datasets from in-situ spacecraft into a validated, machine learning (ML)-ready dataset consisting of solar wind parameters spanning the heliosphere. We focus on the fundamental plasma parameters (i.e., density, velocity, temperature, and magnetic field) and those derived therefrom (e.g., plasma beta). Our work has two phases. In Phase 1, we will compile and validate trends in these parameters with distance from the Sun. In Phase 2, we will extend these trends to include not only solar distance but also heliographic latitude. We will publicly release our merged, averaged, and ML-ready data along with our best-fit analytic models for these trends. These analytic models will provide summaries that can be readily utilized for initializing and validating global heliospheric simulations as well as for planning future deep-space missions.

Background. With advances in high-performance computing, global simulations can offer detailed predictions for variations in solar-wind plasma across the heliosphere. Initializing and validating these simulations with data from in-situ spacecraft can be challenging since such measurements are inherently localized. A vast network of in-situ spacecraft spanning the heliosphere would address this issue and revolutionize our understanding of the solar wind, but such a mission is entirely impractical. Nevertheless, many in-situ spacecraft have been sent across the heliosphere. After suitable adjustments for inter-calibration and solar cycle, their data can be taken together to reveal information about the solar wind's large-scale, average expansion -- the background" on top of which transient events (e.g., CMEs and CIRs) develop.

Data and Methodology. We will aggregate publicly available historical datasets from multiple spacecraft, including Parker Solar Probe (PSP), Helios 1 & 2, Mariner 2 & 10, Ulysses, Cassini, Pioneer 10 & 11, New Horizons, and Voyager 1 & 2. Measurements from these spacecraft span three orders of magnitude in solar distance across sixty years. We will pre-average each spacecraft's data to a common cadence. Then, using a well-established technique, we will correct for solar-cycle variations by scaling each average measurement by a time-shifted, contemporaneous, 1-au average value from the OMNI dataset. By binning the scaled, averaged data (first with solar distance and then also with heliographic latitude), we will reveal the large-scale, average trends in the solar wind. For ease of use, we will characterize these trends by using modern machine learning techniques, including non-linear chi-squared minimization and Gaussian processes.

James Mason/University Of Colorado, Boulder
Solar Dynamics Observatory Machine Learning Dataset (SDOML) Improvements

Since the publication of A Machine-learning Data Set Prepared from the NASA Solar Dynamics Observatory Mission" (herein called SDOML) in 2019, there has been a new publication using this dataset every other month. The utility of having the data of all three instruments onboard SDO wrapped up into one uniform package with the data already cleaned is clear. However, as key members of the team that originated this dataset, we have identified improvements that should be made that would further increase the utility, ease of access, and therefore science return. We will focus primarily on 4 new improvements, resulting in the release of SDOMLv2. First, we will repacketize all of the data into the .zarr format. This is a new, well-supported format specifically designed for handling large, multi-dimensional arrays, especially for use in cloud computing. It is the preferred format for platforms such as Pangeo. This will enable faster manipulation of the data for users. Second, we will generate the synthetic SDO/EVE emission lines data product for the entire timespan of the dataset (2010-2021) at full cadence (6 minutes, the SDO/AIA cadence). This method accepts SDO/AIA data as input and has already been demonstrated in case studies. SDO/EVE's 60-360 Å channel ceased functioning in 2014. This new synthetic data restoration will re-enable all of the scientific analyses that this channel previously afforded, for example irradiance coronal dimming studies that this proposal's PI is heavily invested in. Third, we will include the full, cleaned SDO/EVE spectra in the dataset. SDOMLv1 only includes the extracted emission lines product. This will enable more detailed scientific analyses that require the full spectrum, such as the study of Doppler shifts during eruptions. Finally, we will build open source tools and an example gallery to demonstrate the access, manipulation, and some use cases for SDOMLv2, with emphasis on cloud computing.

We will deliver the dataset itself to the Stanford Digital Repository where SDOMLv1 is stored. We will also deliver the dataset to NASA's Solar Data Analysis Center (SDAC), leveraging our team's existing relationship with the team at Goddard Space Flight Center that maintains that resource. Based on SDOMLv1 and the changes described above, we anticipate the dataset will be approximately 10 TB. Delivery preparation will begin in Project Year 2 and be completed by the conclusion of the period of performance (2023-08-31). The example gallery and open source tools will be hosted on GitHub and be publicly accessible through the duration of the proposed effort and afterwards.

SDO is an exemplar of big data and as such is a perfect fit for many existing AI tools. As a flagship, the high profile means that big scientific returns can be expected from modest effort to make the data more easily accessible to those AI tools. Moreover, SDO's status as a flagship means that it has a big community impact when it sets the example for establishing datasets and tools like SDOMLv2, which helps establish such practices as the norm for all missions in heliophysics.

Xing Meng/Jet Propulsion Laboratory
A Retrospective Analysis Toolbox for Ionospheric Total Electron Content Maps

SCIENCE GOALS
Regional and global ionospheric total electron content (TEC) maps have been routinely produced and made publicly accessible by several research institutions around the world. These TEC maps are obtained from Global Navigation Satellite System (GNSS)

measurements using different satellite constellations and selected networks of ground receivers. TEC maps are one of the key ionospheric datasets for understanding height-integrated ionospheric dynamics at various spatial and temporal resolutions. Recently, improvements in TEC data processing over areas of dense ground receiver distributions open possibilities of robust analysis of ionospheric structuring. However, comprehensive analysis of ionospheric structuring over two decades of TEC maps is currently lacking due to large data volume. Corresponding analysis tools are yet to be tailored to apply to the TEC map dataset. Characterizing key features on TEC maps and understanding their dynamic coupling with external drivers can significantly benefit space weather forecasting. The goal of the investigation is to design a software toolbox for analyzing ionospheric TEC maps retrospectively. The toolbox will be able to identify local regions of elevated TEC from TEC maps, extract characteristic features of the TEC enhancement regions, and diagnose solar and interplanetary driving of the TEC intensification. The objectives of the investigation are: 1) Develop existing image-processing programs to extract features of local TEC intensifications on both global and regional TEC maps and 2) Implement transfer entropy to analyze the connection from solar and interplanetary conditions to the extracted features of the local TEC intensifications.

METHODOLOGY
We will address the objectives by building on, improving, and integrating our existing software of feature extraction and transfer entropy. First, we will will extend the existing feature extraction program to output not only the number of TEC intensifications but also characteristics of the TEC intensifications. Second, we will implement a normalized transfer entropy calculator to compute the normalized transfer entropy from the F10.7 and solar wind data to the identified TEC intensifications.This will reveal any non-linear correlation and predictive information transfer from the solar/interplanetary conditions to the TEC intensifications. The feature extraction program and the normalized transfer entropy calculator construct the toolbox. We will test the toolbox for global TEC maps and regional TEC maps of various spatial resolutions during solar maximum and solar minimum years.

DELIVERABLES
Our toolbox will be made available to the community and applicable for analyzing TEC maps produced by any research institution. We will deliver the toolbox, including the feature extraction program and the normalized transfer entropy calculator, to GitHub and to the CCMC as one of the LWS supported tools and methods (https://ccmc.gsfc.nasa.gov/lwsrepository/index.php). The expected delivery date is April and May 2023.

RELEVANCE
The investigation is highly relevant to the LWS Objective 1 Space Science: LWS quantifies the physics, dynamics, and behavior of the sun-Earth system over the 11-year solar cycle.". It also addresses the two of the three overarching science goals of NASA's Heliophysics program: Advance our understanding of the connections that link the Sun, the Earth, planetary space environments, and the outer reaches of our solar system" and

Develop the knowledge and capability to detect and predict extreme conditions in space to protect life and society and to safeguard human and robotic explorers beyond Earth".

Brian Thomas/NASA Goddard Space Flight Center
Using Machine Learning to Detect and Build CME Datasets for Heliophysics

Using Machine Learning to Detect and Build CME Datasets for Heliophysics

We plan to develop a Machine Learning (ML) based solution to identify physical properties of coronal mass ejections (CME). Our approach will provide a long baseline catalog of CME detections for SOHO with derived properties which we can use to better understand the population of CME relative to solar cycle and other physical phenomena. An ML-created catalog solves weaknesses found in other automated catalogs and in manual catalogs. In addition to this catalog of CME events we will also provide the ML models which encapsulate SME expertise for identifying CME. These may be utilized to better detect CME for space weather forecasting and to compare observational data with numerical models and thereby serve to better quantify simulation performance and sidestep human bias in comparison. To perform this work we will utilize computer vision, a field of artificial intelligence that trains computers to interpret and understand images.

We will supply these derived events as a VOEvent formatted file to the Solar Data Analysis Center (SDAC) on or by May 2023. ML models based on YOLO computer vision algorithm and the associated python code for creating and running them will be released as open software on the NASA GitHub (https://github.com/nasa/).

Benoit Tremblay/University Of Colorado, Boulder
Deep Learning for Ensembles of High-Resolution and High-Cadence Transverse Velocity Maps as High-Level Data Products

Knowledge of flows in the solar photosphere is crucial for understanding many aspects of solar physics, from processes in the interior to coronal heating and eruptions. While velocities along the line-of-sight are a common data product derived from spectropolarimetric observations, transverse velocities are not. The aim of this proposal is to provide tools to compute transverse flows from observations and enable science relevant to the Living with a Star (LWS) program, including the study of energy transport from the photosphere to the atmosphere where it can be released in the form of space weather events, and the derivation of realistic boundary conditions for data-driven simulations of the atmosphere necessary for studying these events.

There are three main groups of methods to infer transverse flows from observations. Tracking methods (e.g., Local Correlation Tracking, Balltracking) measure optical flows typically from intensitygrams in the Quiet Sun and magnetograms in active regions.

Physics-based methods use magnetograms and Dopplergrams and solve the magnetic induction equation (e.g., PDFI, DAVE4VM) to infer flows in typically active regions. Finally, the DeepVel & DeepVelU deep learning methods use magnetohydrodynamics (MHD) simulations and a combination of intensitygrams, magnetograms, and Dopplergrams of Quiet Sun or a active region to infer depth-dependent transverse velocities. Through supervised learning, the neural network emulates flows, and by extension the full set of MHD equations, from the training simulation. Recently, we trained DeepVel using simulation data with spatial resolutions and cadences comparable to instruments like SDO/HMI, DST/IBIS, SUNRISE/IMaX, and DKIST/VBI. Our tests using model data have yielded promising results (Tremblay et al., 2021). For example, using DeepVel, we were able to recover flows in the Quiet Sun at subgranular spatial and temporal scales where optical flows decorrelate from physical flows. While these results are encouraging, there remain improvements before DeepVel can confidently be applied to observations. Although simulations have become increasingly realistic, the validity of model-dependent flows inferred through deep learning needs to be addressed thoroughly.

With this proposal, we plan to: (1) Prepare instrument-specific versions of DeepVel trained on an ensemble of state-of-the-art radiative-MHD simulations of granulation, pores, and sunspots to be gathered from the community; (2) Use combinations of inputs (intensitygrams, magnetograms, Dopplergrams) and provide physical interpretations of the results; (3) Improve preprocessing (spatial sampling, PSF convolution, etc.) to project from the model space to the observations space; (4) Assess realism of flows inferred through deep learning by comparing to tracking methods (e.g., FLCT, Balltracking) in weak-field regions and physics-based methods (e.g., PDFI) in strong-field regions; (5) Estimate errors; (6) Experiment with neural network architectures and training, like the development of a physics-informed neural network to generate flows constrained by the induction equation in strong-field regions and by a continuity or transport equation in weak-field regions.

The aim of this proposal is to provide the community with tools to generate realistic transverse velocity maps. We will make the codes available on Github with Jupyter notebook tutorials by 11/01/23. The proposed tools will enhance the scientific output from heliophysics missions (e.g., SDO, Hinode) and target the transport of plasma and magnetic energy, thus addressing LWS objective #1, quantify the physics, dynamics, and behavior of the Sun-Earth system over the 11-year solar cycle", and key goal #4 of the 2013-2022 Heliophysics Decadal Survey Advances in understanding of solar and space physics require the capability to characterize fundamental physical processes that govern how energy and matter are transported."

Jia Yue/Catholic University Of America
Machine learning based automatic detection of upper atmosphere gravity waves from NASA satellite images

Severe weather such as thunderstorms, cold fronts, and hurricanes, excite atmospheric gravity waves (AGWs) that can propagate into the Earth's upper atmosphere. AGWs play key roles in the dynamics and energetics of the mesosphere and thermosphere. They also induce space weather conditions by driving traveling ionosphere disturbances (TIDs) and seeding spread F and plasma bubbles. AGWs imprint their traces in the airglow layers which are several faint emission layers in the mesopause region. AGWs in the upper atmosphere have strong negative correlation with the 11-year solar cycle and the reason is unknown. On the other hand, climate change in the lower atmosphere may change AGW excitations. However, to date, there have been very few satellite observations of global AGWs in the mesopause region. This lack of information about the global AGWs below the E-region ionosphere and lower thermosphere has limited our ability to quantify the impact of AGWs on space weather. Therefore, we propose to undertake a machine learning detection of AGWs in airglow from 10+ years of NASA VIIRS/Day Night Band (DNB) images obtained by two satellites, Suomi NPP and NOAA20 and disseminate the data and algorithm via SPDF. The rich AGW data gained from this work will enable statistical characterization of global AGW morphology in the mesopause region and its solar cycle and long-term variations.
We will build Convolutional Neural Network (CNN) based deep learning models to extract AGW features from DNB images. CNN model is the state-of-the-art technique to classify images and has been widely used in many image detection/classification problems. It typically contains convolutional layer, pooling layer, activation layer such as Rectified Linear Unit (ReLU), fully connected layer, and loss layer in order to capture spatial structure of data in model training. To train CNN models such as 19-layer VGGNet and 50-layer ResNet for AGW detection, we will manually label thousands of images, both with and without AGWs for the training set, and a tenth of the images will be left unused to validate the training model. The training set will be prepared by manually labeling the wave pattern in the wave-containing image. By training the CNN models from the manually labeled images, the models will be able to automatically locate wave patterns and enable us to extract a sub-matrix full of wave patterns from millions of satellite images.

The proposing team combines satellite data processing expertise in both NASA Heliophysics and Earth Sciences, expert in AGW physics, and data science experience in machine learning. The proposed work is listed in the 2021 Heliophysics-LWS Tools announcement: Leverage current technology for the discovery, access, and effective use of NASA's data, as well as enable new technology and analysis techniques for scientific discovery in areas of Heliophysics research covered by LWS objective, quantifies the physics, dynamics, and behavior of the sun-Earth system over the 11-year solar cycle. This work strongly supports the scientific goal emphasized by the 2013-2023 Decadal Survey in Solar and Space Physics, Determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs." The machine learning algorithm will also be shared with the NASA WAVE mission.

Deliverables to SPDF by July 2023: ~5000 GW images along with corresponding raw VIIRS data; source codes of image classification and localization models; visualization tools.

Heliophysics Innovation in Technology and Science
Abstracts of selected proposals
(NNH21ZDA001N-HITS)

Below are the abstracts of proposals selected for funding for the HITS program. Principal Investigator (PI) name, institution, and proposal title are also included. Nine (9) proposals were received in response to this opportunity, six (6) of which were selected for funding.

Lauren Blum/LASP Space Science Building SPSC
Space Weather Instruments for the SWAP-E CubeSat Constellation Flight Opportunity

This project aims to develop and build two miniaturized scientific instruments for an upcoming flight opportunity in early 2023. The company NearSpace Launch has been funded through NASA's SBIR program to develop the SWAP-E mission, a constellation of ThinSats" (a version of CubeSats), which will provide real-time data through the Globalstar network and have space available for scientific payloads. This proposal aims to capitalize on this unique flight opportunity to miniaturize, build, and fly two scientific instruments: the High Energy Particle (HEP) Telescope and Rapid Active Plasma Sounder (RAPS). Results of this will provide flight heritage for new, miniaturized instrumentation as well as unique multipoint measurements of the plasma, wave, and energetic particle environment at altitudes below 400km, a region not often probed by spacecraft.

The HEP instrument will measure energetic electrons ranging from ~500keV   3 MeV and is a modified version of the REPTile energetic particle telescope flown on the Colorado Space Weather Experiment (CSSWE) CubeSat (Li et al. 2013 JGR, Blum and Schiller 2012 AIAA/USU, Schiller et al. 2013 IEEE). It will include an additional instrument aperture to enable simultaneous measurement of both downgoing and upgoing electrons. With one aperture aligned with the zenith direction, looking up the magnetic field line to measure precipitation of radiation belt electrons, the other looking down towards Earth to measure the backscattered electron population, to better quantify the fraction of electrons truly lost to the atmosphere at any one time.

The RAPS instrument will enable novel studies of trans-ionospheric propagation of Very Low Frequency (VLF) whistler-mode plasma waves. RAPS simultaneously samples VLF wave power (~300 to ~40 kHz) up to 300 spectra/s and density fluctuations up to 1,000 samples/s, thereby resolving spatial scales as small as 10 m. RAPS analog and digital designs draw heritage from Langmuir Probe and Waves (LPW) instrument currently operating on the MAVEN Mars mission (Andersson et al., 2015) and recent LASP internal research and development (IRD) efforts to produce a stand-alone relaxation sounder and VLF receiver within a CubeSat resource profile.

Relevance to NASA and HITS program:
The proposed work will produce unique measurements of energetic particle precipitation, whistler mode waves, and plasma density of the low altitude (<400km) environment at Earth, providing important information for both scientific understanding as well as space weather monitoring of this region. With the proliferation of CubeSats and SmallSats in recent years, miniaturization of the two proposed instruments, HEP and RAPS, will enable future SmallSat and constellation missions. Multi-point particle and wave measurements from affordable constellation missions will provide new insight into the spatial and temporal evolution of these phenomena. Taking advantage of this unique, quick turn-around flight opportunity to raise these instruments to TRL 9 and provide flight heritage will be critical for paving the way for future missions. Additionally, the measurements obtained from HEP and RAPS from the SWAP-E mission will result in new understanding of the particle and wave environment at altitudes below 400km, a region not often probed by spacecraft. Ionospheric density irregularities and energetic particle precipitation are two key space weather phenomena. Low latency measurements of these processes provided by the SWAP-E mission will be important for monitoring phenomena including Global Navigation Satellite System (GNSS) scintillation and radiation effects on satellites.

Alexander Engell/NextGen Federal Systems
Extend Open Source Software to Streamline Heliophysics Data Analysis

Heliophysics is continually growing the volume and complexity of data amassed due to new missions and more sophisticated models. Meeting the science objective to perform efficient data discovery is challenging because of the large volume of disparate data in multiple formats. Cloud-friendly data access, visualization, annotation, and analysis of terabytes and even petabytes of data are critical to overcome this challenge. Innovative software is a cornerstone component and pathway to improving these abilities.

Existing state of the art open-source software can be extended to improve its already powerful abilities to access, stream, annotate and analyze data. NextGen Federal Systems (NextGen), in collaboration with Anaconda, Inc., is excited to propose enhanced software libraries that will streamline how scientists access, visualize, interrogate and analyze heliophysics and astrophysics imagery and time-series data.

Improvements to the Bokeh, fsspec, and related software libraries, accessing and visualization of imagery and time-series datasets, benchmarking, and developing dashboards will be executed within the cloud-native Space Radiation Intelligence System (SPRINTS; Engell et al., 2017). SPRINTS will act as the workflow environment to achieve the software product development objective and apply it to the data. Collectively, the improved software libraries and SPRINTS infrastructure will be bundled into a new Panhelio" environment. Panhelio shares parallel goals to the Earth Science's Pangeo project (Abernathey et al., 2017):

1. Foster collaboration around the open-source scientific python ecosystem for solar / inter-planetary / magnetospheric / ionospheric science
2. Support the development with domain-specific helioscience packages
3. Improve scalability of these tools to handle PB-scale datasets on HPC and cloud platforms

This effort will collectively forge a streamlined and scalable capability for heliophysics researchers to access, stream, visualize, interrogate, annotate, analyze, and conduct Machine Learned (ML) processes; thereby improving the data enterprise and all associated science in support of the HITS objectives.

Subhamoy Chatterjee/Southwest Research institute

Community-driven Self-Supervised Learning on SDO data: feature exploration with largely unlabeled data

The Solar Dynamics Observatory (SDO) has revolutionized the field of heliophysics by recording 1-2 TB data/day and having a nominal lifetime data volume of > 1000 PetaBytes. Labeling such data requires a monumental effort, but novel techniques of machine learning can help lessen
this load significantly. Here we propose to apply self-supervised learning (SSL), on large amount of unlabeled SDO data, to find clusters of solar images representing similar features. Furthermore, in an age of increasingly open-source collaborative frameworks, the
democratization of machine learning presents the heliophysics community with an invaluable opportunity to broaden and deepen the development of programs aimed at collaborating with the general public. Here we propose to create a pilot program for the involvement of the
general public in the development and application of machine learning algorithms to address heliophysics needs. We structure our project around the following objectives:
O1 Community-driven preparation of machine learning ready unlabeled SDO image data
O2 Community-driven training and deployment of a self-supervised learner to find clusters of similar SDO image features

DATA: We use the publicly available SDO/AIA images and SDO/HMI line-of-sight magnetograms
for our project.

METHODOLOGY: We build 3 teams consisting of people with no prior knowledge in either heliophysics or machine learning (ML) and drive them towards accomplishing 3 tasks namely (1) development of SDO data downloader, (2) cleaning and producing ML-ready SDO dataset and (3)
Training and deploying a self-supervised learner to find clusters of similar SDO images. The first team studies available python tools (e.g. Fido from SunPy) to download SDO

data and tries to add additional layers to simply the search and download process. The second team first studies the
publicly available SDO-ML dataset that is produced by applying multiple corrections and spatiotemporal downsampling on level-1 SDO data. The team members then use similar transformations on SDO data, downloaded by team-1, without downsampling and divide the full-disc images into
tiles representing various solar features. This gives closure to O1. The third team takes those tiles and trains self-seupervised learners (SSLs) to derive clusters of similar images by comparing featuring embeddings. This team also creates a bank of those feature embeddings and develops a
fast image search tool. The search tool accepts image query and uses nearest neighbour search to fetch similar images from the embedding bank. This gives closure to O2.

WHY HITS? Our project aims to develop a program for the application of Machine Learning (ML) to heliophysics that can be easily scaled up, by involving an increasingly proficient community and the application of effective management methodologies and powerful collaboration techniques.
We start with three research teams in the understanding that each of these pilot members can become leaders of subsequent cohorts producing an exponential growth of our program further down the line.
Our project also has the potential to revolutionize the way we interact with SDO images for scientific applications. Traditional clustering approaches require a significant feature engineering effort to identify and group similar data. Our approach exploiting self-supervised learners enables
the direct use of images as queries to extract large banks of similar images, allowing faster cataloging of data without manual intervention. This will also accelerate scientific discoveries that rely on such large multi-modal solar data. HITS is the perfect opportunity for a project such as ours, in which there is a joint development of community collaboration protocols and the implementation of novel ML techniques.

Chuanfei Dong/Princeton University
Integration of Kinetic Effects in Multi-Moment Multi-Fluid Models through Machine Learning

Science goals and objectives: Our understanding of Earth's magnetosphere has been significantly advanced by increasingly sophisticated numerical models. However, most of the global magnetosphere models cannot accurately treat collisionless magnetic reconnection - a key process controlling magnetospheric dynamics - due to their lack of electron physics and/or other non-ideal effects. Therefore, integrating kinetic effects in fluid-based plasma models is crucial and urgent for global magnetosphere modeling. To achieve this goal, we have developed a multi-moment multi-fluid model that is capable of reproducing certain critical aspects of collisionless reconnection physics from fully kinetic simulations. In the multi-moment approach, one needs a fluid closure to close the system of equations. As an example, closures that can capture Landau damping have been demonstrated to be successful in both fusion and space plasma research, but the closures are numerically challenging for global simulations due to their non-local nature. Meanwhile, machine learning (ML) has made significant progress and started having impacts on physical science and research. These lead to the primary science objectives of the proposed work: (1) to generate a machine learning surrogate model of fluid closure that incorporates kinetic effects for large-scale fluid simulations, yielding accurate and efficient solutions, and (2) to explore strategies to utilize data-driven, multi-moment multi-fluid models for global magnetosphere modeling.

Methodology: We will utilize the Gkeyll modeling framework in conjunction with machine learning to integrate kinetic effects in fluid-based plasma models. Gkeyll Vlasov-Maxwell (V-M) model is a fully kinetic model that solves the distribution function of charged particles in the six-dimensional (6-D) phase space. Gkeyll ten-moment multi-fluid model contains non-ideal effects like the Hall effect, electron inertia, and non-isotropic/non-gyrotropic pressures. Both have been applied to study different plasma physics problems such as magnetic reconnection. In order to obtain an optimal fluid closure (i.e., the relation between pressure tensor and heat flux tensor for the ten-moment model), we will first run a large number of local V-M simulations of magnetic reconnection with parameters guided by magnetospheric observations. Subsequently, we will construct and train the neural networks to learn the fluid closure from the V-M data. Eventually, we will couple the machine-learned fluid closure to the Gkeyll ten-moment multi-fluid model to study collisionless magnetic reconnection in an accurate but affordable way.

Relevance: In this proposal, we propose an innovative and novel idea to integrate kinetic effects in fluid-based plasma models to advance Heliophysics research that can be accomplished in one year. After demonstrating the feasibility of our approach, we plan to submit another proposal to a ROSES element in a subsequent year. Our proposal will offer the possibility for major scientific breakthroughs and new approaches to gaining knowledge and understanding of Earth's global magnetosphere. Given that magnetic reconnection is a key process controlling Earth's magnetospheric dynamic during solar wind interaction and a fundamental process throughout the universe, this proposal directly addresses the last two goals of the most recent Heliophysics Decadal Survey for Solar and Space Physics: to determine the interaction of the Sun with the Solar System and the interstellar medium" and to discover and characterize fundamental processes that occur both within the heliosphere and throughout the Universe."

Viacheslav Sadykov/Georgia State University
Data Discoverability and Machine Learning Readiness for Understanding Space Radiation in Earth Environment

Variations of the radiation environment at the Earth's atmosphere are coupled to processes driven by solar activity on long timescales (11-year) and transient events (e.g., flares, coronal mass ejections, solar energetic particles, ionospheric scintillations). The increase of radiation can elevate aircraft crew exposure and affect onboard systems, therefore understanding the present state of the radiation environment and its prediction is critical for aircraft crew safety. Continuous monitoring of the radiation environment evolution is crucial for developing reliable nowcast and forecast systems to mitigate radiation exposure. Therefore, it becomes critical to organize the corresponding data from different sources and develop a user-friendly platform that will allow to perform an initial analysis of the data and retrieve them in a user-specified format.

The primary goal of the proposed investigation is to enhance understanding of how space radiation (in the form of the Galactic Cosmic Rays, GCRs, and Solar Energetic Particles, SEPs) interacts with the Earth's Environment. The goal will be achieved by pursuing three specific objectives: 1) expansion of the previously-developed Radiation Data Portal (RDP) database, through the integration of new data sources relevant to the space and Earth radiation environment, and providing a convenient API-based access to these sources, 2) upgrade of the RDP search and visualization capabilities and 3) preparation of the machine learning-ready (ML-ready) data set for machine learning-driven models based on the accumulated data sources and available NAIRAS model of Earth's radiation environment.

The following data sources are proposed to be integrated into RDP: 1) ARMAS in-flight radiation measurements obtained after October 4, 2020; 2) the neutron monitor data from ground-based stations; 3) geomagnetic activity data from NASA's CDAW; 4) the NASA Advanced Composition Explorer (ACE) and Deep Space Climate Observatory (DSCOVR) measurements; 5) Cosmic Ray Muon monitor data by muon telescopes at GSU; 6) enhanced GOES proton and electron data; 7) Solar and Heliophysics Observatory (SOHO) EPHIN electron flux measurements; and 8) NAIRAS models supporting ARMAS flights.

The proposed research potentially has a long-lasting impact on the community. The proposed objectives allow one to access the radiation environment data faster and easier, study the causal relations and understand the radiation environment better. The project will provide a starting platform for an enhancement of data-driven machine learning modeling based on sparse data sampling (e.g., radiation measurements during flights), which will encourage and foster machine learning-driven nowcasting of the radiation environment. The outcomes of this project are important not only from the research purposes but also from the operational and commercial points of view. Governmental agencies committed to space weather understanding and forecastings such as NASA and NOAA, as well as private companies such as aerospace corporations and airlines, are the potential users of the data portal. Therefore, implementation of the proposed capabilities supported with the advanced search engine, visualization, and data retrieval tools will provide a solid foundation to address a wide range of space weather-related problems such as monitoring, nowcasting, and forecasting the radiation environment at the different temporal and spatial scales.

Shadia Habbal/Institute for Astronomy
KITE-BORNE PLATFORM FOR TOTAL SOLAR ECLIPSE SPECTROSCOPIC OBSERVATIONS OF THE CORONA AND THE SOURCES OF THE SOLAR WIND

Science Objectives: Total solar eclipses continue to offer unique observing opportunities to explore the physical properties of the corona, namely the outer atmosphere of the Sun, and the processes by which the corona expands into space as the solar wind. Direct imaging and spectroscopy in the optical part of the spectrum are the only tools available to probe the distance range of a few solar radii above the visible limb of the Sun. In this radial span, magnetic fields and plasmas undergo their most pronounced changes, thus establishing the observed features of coronal structures and the properties of their quiescent and dynamic behavior at the sources of the solar wind. An imaging spectrometer offers the most comprehensive remote sensing tool to infer the temperature, density and abundance of the different ionic species, and their velocities along the line of sight. Such parameters are essential for exploring the physical processes defining the corona and the sources of the solar wind. The scientific and technological objective of this proposal is to utilize a kite-borne platform for an imaging spectrometer to mitigate low lying clouds during total solar eclipse observations.
Methods and Techniques. The technical approach is to evaluate the performance of ALIMAS, a pseudo 3-channel spectrometer operating from a kite-borne platform flying above clouds at an altitude not to exceed 4000 m, during total solar eclipses. The design of the spectrometer is based on the demonstrated heritage of a multi-channel, partially multiplexed imaging spectrometer, PAMIS, which operated successfully during the eclipses of 2015, 2017 and 2019. ALIMAS covers a wavelength range of 400 to 1100 nm and operates in high order. Tracking the Sun prior to totality and spectroscopically imaging the corona during totality, will be achieved with a 2-mirror coelostat system mounted on a rotating platform which channels light into the fixed entrance lens of the spectrometer. The payload will be enclosed in a streamlined waterproof box. The kite and tether will be based on the Dyneema Double Delta Conyne (DDC) design and Dyneema tether line developed by USRI, with a wing span of 7.2 m. Launched with the use of a winch, the kite will remain tethered to the ground thus enabling the retrieval of the payload at the end of the eclipse observations.
Perceived Significance: The proposed kite-borne platform aimed at mitigating the presence of clouds for total solar eclipse spectroscopic observations, is an urgent and expeditious research activity, which takes full advantage of the NASA HITS initiatives. This innovative approach will capitalize on the upcoming total solar eclipse of 20 April 2023 over north-western Australia, to test its viability for the longer 4 April 2024 total solar eclipse across the US. This novel technology will be a solid step forward to expand the capabilities and viability of tethered aerial platforms, combined with modern instrumentation, for Solar and Heliospheric observations, and for atmospheric and remote sensing measurements in Earth and Planetary Sciences. It also offers key benefits for the emerging tethered aerosystem community at large. The proposed project serves as an inspiring example of the more affordable and accessible aerial-based systems for the next generation of young aspiring scientists. This proposal addresses NASA's Heliophysics goals to Understand the Sun and its interactions with the Earth and the Solar System,

including space weather" and supports Investigations of the origin and behavior of the solar wind and transient structures".

Heliophysics Living with a Star Infrastructure
Abstracts of selected proposals
(NNH21ZDA001N-LWSIS)

Below is the abstract of the proposals selected for funding for the LWSIS program. Principal Investigator (PI) name, institution, and proposal title are also included. 1 proposal was received in response to this opportunity. On February, 2, 2022, 1 proposal was selected for funding.

Hanne Mauriello/University Corporation For Atmospheric Research (UCAR)
Heliophysics: Living with a Star Strategic Capabilities

This proposal outlines continuing collaborations between UCAR and NASA for work in support of NASA Heliophysics Living With a Star Infrastructure. CPAESS will continue best practices learned over the past five years (2016-2021) for program management of a new NASA Cooperative Agreement and will bring new levels of innovation and efficiency to the collaboration.

As an inherently multidisciplinary science, heliophysics requires a concerted effort to bring expertise from across disciplines to bear on complex scientific endeavors. Many advances in our understanding of the heliospheric system have been in areas that cross traditional disciplinary boundaries. CPAESS proposes to strengthen the scientific workforce entering heliophysics research by leveraging its expertise and its years of experience in administration and management of summer institutes and postdoctoral programs. For this RFP, CPAESS proposes:

A re-envisioned structure for the Heliophysics Summer School that utilizes both remote and in-person phases to maximize participation and engagement

An enhancement of the mentorship process to further strengthen the successful Jack Eddy Postdoctoral Fellowship Program

Expanded outreach to faculty at heliophysics-related disciplines at Minority-Serving Institutions (MSIs), thus bolstering the pool of potential applicants from underrepresented groups for the summer school and postdoctoral program. Community-building activities to help build the interdisciplinary, international networks that are at the core of heliophysics research.
