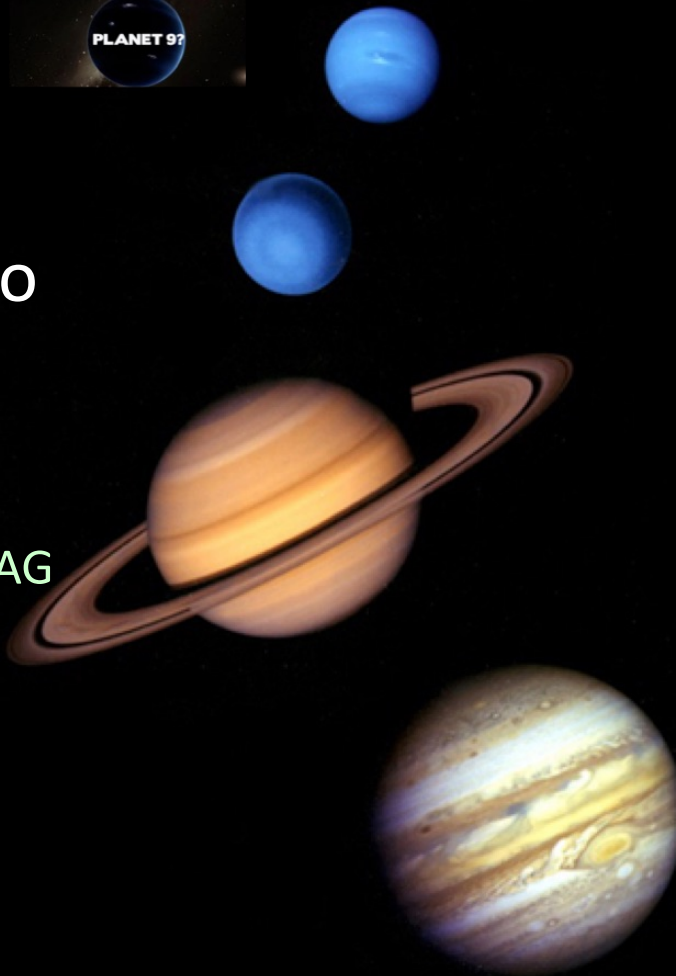


Outer Solar System: Many Worlds to Explore

OPAG Update to PAC

23 Feb 2018

Alfred McEwen and OPAG
Steering Committee

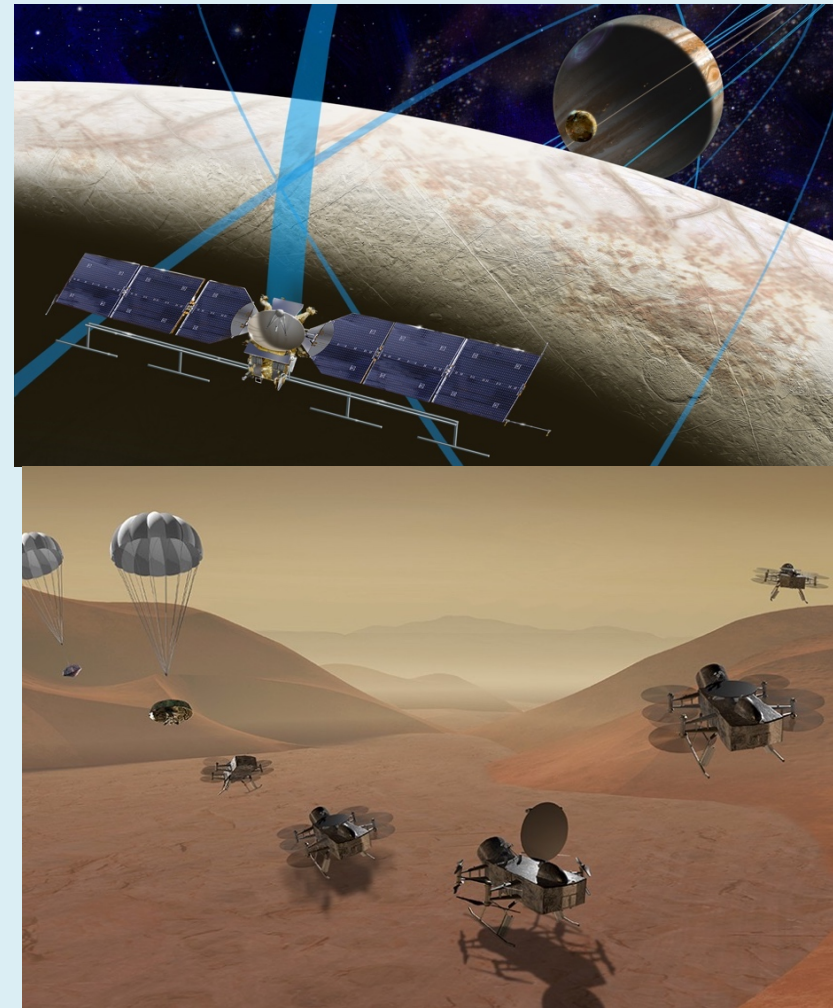


Outer Planets Assessment Group (OPAG) Charter

- **OPAG is NASA's community-based forum designed to provide science input for planning and prioritizing outer planet exploration activities for the next several decades.** It is chartered by NASA's Planetary Science Division (PSD) and reports its findings at meetings of the Planetary Science Advisory Committee (PAC) of the NASA Space Science Advisory Committee (NAC).
- **Open to all interested scientists and others,** OPAG regularly evaluates outer solar system exploration goals, objectives, investigations and required measurements on the basis of the widest possible community outreach.
- **OPAG meets twice per year,** summer and winter. We provide “input” (findings) to NASA, but we do not make “recommendations” to NASA.
- **OPAG presentations to various National Academies studies**
- **OPAG documents are input to Decadal Surveys.**
- *Steering Committee membership is nominally for 3 years, but can be extended for up to 3 additional years.*
- OPAG covers outer planet systems; SBAG covers small bodies
 - *Joint custody of Pluto system and other dwarf planets in Kuiper Belt*

Key Activities since Final PSS Meeting

- Cassini mission ended Sept. 15th, 2017 with plunge into Saturn
- Dragonfly selected for New Frontiers Step 2, Zibi Turtle (PI)
- Juno Probe Completed 10th Science Flyby of Jupiter
- Europa Clipper progressing towards PDR
- JUICE progressing towards 2022 launch
- Europa Lander SDT and pre-phase A studies
- Ice Giants SDT study completed
- Roadmap to Ocean Worlds (ROW)
- **Revised draft Goals Document posted**



OPAG Findings: Sept. 2017, Scripps Inst. Oceanography

1. **Current Missions**: Cassini, Juno, New Horizons: OPAG applauds spectacular successes, asks NASA to adequately support associated data analysis programs.
2. **Europa Lander**: Support NASA's decision to proceed methodically, working to understand science, technology, and cost during Pre-Phase A study. Urge NASA to obtain best possible advice from science community on decisions impacting SDT science objectives and to clarify schedule and plans for Lander instrument PEA.
3. **Exploration of Ice Giant Systems**: Pursue development of an Ice Giant Flagship mission as soon as budget allows. Encourage completion of eMMRTG and HEEET technology development. Encourage involvement of international partners.
4. **Discovery AO**: Announce expected date of AO and key mission constraints as soon as possible.
5. **Technology**: Suggests both PESTO and RPS offices work closely with OPAG to develop rationale and guidance for their programs since needs of outer planets community often drive technologies developed.

OPAG Findings: Sept. 2017

6. **Mission studies in preparation for upcoming decadal survey**: Supports early initiation of mission studies in preparation for upcoming decadal survey. Clarify process NASA intends to use for identifying targets for mission studies, how previous decadal survey studies will be taken into account, and timeline for performing studies.
7. **Building connections between outer planets and Earth oceanography communities**: Encourage NASA to emphasize connections between Earth and outer solar system ocean worlds. Support appointment of an ocean world scientist at NASA to enhance interactions between NASA, ocean agencies and research communities.
8. **Status of Cassini DAP and New Frontiers DAP**: Request that NASA assign a dedicated PSD manager to CDAP and NFDAP programs to ensure programs remain viable now and in the future.
9. **Diversity and Unconscious Bias**: Request that NASA brief OPAG on PSD's work on mitigating biases in proposal review activity.

New Findings for February 2018

- OPAG met Feb 21-22 in Hampton, VA
- Findings are in revision—will send to PAC when posted

OPAG Draft Goals Document: 2018

- First goals document from 2006
- Previously posted draft update: Nov 2015
 - Outer planets community facing “Decade of Darkness” after end of Cassini and Juno (both expected in 2017)
- The current outlook is much improved
 - Europa Clipper approaching PDR, arrive at Jupiter sometime from 2025-2032
 - Juno extended missions
 - Dragonfly Titan mission in Phase A for New Frontiers
 - SDT studies of Europa Lander and Ice Giant missions
 - Congressional language to formulate Ocean Worlds program
- There will still be a significant gap before Europa Clipper arrives at Jupiter
- Draft update released for community comments:
<https://www.lpi.usra.edu/opag/>

Changes to Draft Goals Document in 2018

- Revised Introduction
 - Ocean Worlds emphasis, but not the only emphasis
- New sections:
 - Planets in the Kuiper Belt
 - Ocean Worlds and the Search for Life
 - OPAG Relevance to Worlds not in the Outer Solar System
 - Telescopic Observations
 - Summary Recommendations for Next Decadal Survey

Scientific Goals for Exploration of the Outer Solar System

Explore Outer Planet Systems and Ocean Worlds

EXECUTIVE SUMMARY

1.0 INTRODUCTION

1.1 The Outer Solar System in Vision and Voyages

1.2 New Emphasis since the Decadal Survey: Exploring Ocean Worlds

2.0 GIANT PLANETS IN OUR SOLAR SYSTEM

2.1 Jupiter and Saturn

2.2 Uranus and Neptune

3.0 GIANT PLANET MAGNETOSPHERES

4.0 GIANT PLANET RING SYSTEMS

5.0 GIANT PLANETS' MOONS

5.1 Pristine/Primitive (Less Evolved?) Satellites' Objectives

5.2 Ganymede Science Objectives

5.3 Europa Science Objectives

5.4 Io Science Objectives

5.5 Enceladus Science Objectives

5.6 Titan Science Objectives

5.7 Triton Science Objectives

6.0 PLANETS IN THE KUIPER BELT

7.0 OCEAN WORLDS AND THE SEARCH FOR LIFE

7.1 Ocean Worlds: Understanding Oceans and Habitability Worlds

8.0 OPAG RELEVANCE TO WORLDS NOT IN THE OUTER SOLAR SYSTEM

9.0 TECHNOLOGY

10.0 TELESCOPIC OBSERVATIONS

11.0 SUMMARY RECOMMENDATIONS FOR NEXT DECADAL SURVEY

Key References

Purposes of Goals Doc

- Frame the science objectives for exploration of the outer solar system.
- Consistent with the 2013 Decadal Survey “Vision and Voyages” but kept up-to-date as new missions are approved, new discoveries are made, models evolve, our understanding of solar system processes changes, and new questions are posed.
- Will be used as a resource for defining technology development directions and needed laboratory experiments, modeling, and other research.
- Resource for mission and instrument science objectives.
- Guide our preparation for the outer solar system portion of the next decadal survey
 - Including mission studies being done in preparation for that survey.
- *The emphasis for future exploration of the outer solar system is to understand giant planet systems and ocean worlds.*

Result	References
Cassini discovery of subsurface water ocean in Titan	Iess et al., Science 337, 2012
Cassini discovery of global subsurface water ocean in Enceladus	Thomas et al., Icarus 264, 2016
HST discovery of probable active plumes on Europa	Roth et al., Science, 2014; Sparks et al., Ap J., 2016; Sparks et al., Ap J., 2017
Cassini discovery that the ocean of Enceladus is probably habitable	Waite et al., Science 356, 2017
New Horizons reveals surprising complexity and activity in Pluto system	Stern et al., Science 350, 2015; many others
Cassini discovery of cloudbursts of methane rain on Titan	Turtle et al., Science 332, 2011 (not cited in V&V)
Active geology & shallow water on Europa	Schmidt et al., Nature 479, 2011 (not cited in V&V)
Detailed analysis of Saturn's quasi-30-year storm in 2010-2011	Many papers
Observation of Saturn's atmospheric seasonal evolution	Many papers including Fletcher et al., Icarus 250, 2015 and Fletcher et al., Icarus 264, 2016
Juno reveals the enormous complexities of Jupiter's atmosphere and interior	Bolton et al., Science 356, 2016
Cassini reveals complexities of Saturn's rings and small inner moonlets.	Many papers
Cassini uses Saturn's rings as a seismometer to study large-scale oscillations in the planet	Hedman and Nicholson, Astron. Jour. 146, 2013
Cassini reveals potential oceans in Dione and Mimas	Hammond et al., Icarus 223, 2013; Tajeddine et al., Science 346, 2014; Beuthe et al., GRL 43, 2016
Galileo reanalysis: plate tectonics on Europa	Kattenhorn and Prockter, Nature Geoscience 7, 2014
HST confirmation of subsurface ocean in Ganymede	Saur et al., JGR-Space Physics, 2015
Voyager reanalysis: Triton's tidal heating and possible ocean	Nimmo and Spencer, Icarus 246, 2015
Uranus and Neptune have different internal structures	Nettelmann et al., Planetary and Space Science 77, 2013
Models explaining how ice giants might avoid becoming gas giants	Frelikh and Murray-Clay, Astron. Jour. 154, 2017; Lambrechts and Lega, A&A 606, 2017
Competing explanations for Uranus' anomalously low internal heat flux	Nettelmann et al., Planetary and Space Science 77, 2013; Kurosaki and Ikoma, Astron. Jour. 153, 2017
Dynamic coupling of dynamos and zonal winds in Uranus and Neptune	Soderlund et al., Icarus 224, 2013
Daily reconnection of Uranus' magnetosphere during summer and winter solstice	Cao and Paty, JGR Space Physics 2017
Hydrothermal water-rock interactions in Enceladus' ocean	Hsu et al., Nature 519, 2015
Enceladus' plume dynamics and implications for origin and transport through the ice shell	Nakajima and Ingersoll, Icarus 272, 2016; Ingersoll and Nakajima, Icarus 272, 2016; Tucker et al., Icarus 257, 2015; Ingersoll and Ewald, 2017, Icarus 282.
Composition and bathymetry of Titan seas	Mastrogiuseppe et al., GRL 41, 2015; Mitchell et al., GRL 42, 2015; Le Gall et al., JGR 121, 2016; Hayes et al., Ann. Rev. Planet. Sci. 44, 2016
Understanding Titan's atmospheric circulation, methane cycle, atmosphere-surface interaction, and composition	Mitchell and Lora, Ann. Rev. Earth Planet. Sci. 44, 2016; Newman et al., Icarus 267, 2016; Charnay et al., Nat. Geos. 8, 2015; de Kok et al., Nature 514, 2014; many others
Potential Production of H ₂ by Radiolysis of Water in the Rocky Cores of Enceladus, Ceres, Europa, Titania, Oberon, Pluto, and Charon	Bouquet et al., Ap. J. Lett. 840, 2017

Many key new science results since V&V was finalized

Crosscutting Science Themes	Priority Questions	Candidate future missions to outer planets
Building new worlds	1. What were the initial stages, conditions, and processes of solar system formation and the nature of the interstellar matter that was incorporated?	Ice Giants mission, KBO mission , Saturn Probe
	2. How did the giant planets and their satellite systems accrete, and is there evidence that they migrated to new orbital positions?	Ice Giants mission, Saturn Probe, Io Observer, multiple Ocean Worlds missions
	3. What governed the accretion, supply of water, chemistry, and internal differentiation of the inner planets and the evolution of their atmospheres, and what roles did bombardment by large projectiles play?	Ice Giants mission, Io Observer, Titan mission (see Section 8.0)
Planetary habitats	4. What were the primordial sources of organic matter, and where does organic synthesis continue today?	Ice Giants mission, multiple Ocean Worlds missions , KBO mission
	5. Did Mars or Venus host ancient aqueous environments conducive to early life, and is there evidence that life emerged?	
	6. Beyond Earth, are there contemporary habitats elsewhere in the solar system with necessary conditions, organic matter, water, energy, and nutrients to sustain life, and do organisms live there now?	Multiple Ocean Worlds missions , Ice Giants mission
Workings of solar systems	7. How do the giant planets serve as laboratories to understand Earth, the solar system, and extrasolar planetary systems?	Ice Giants mission, Saturn probe, multiple Ocean Worlds missions, Io Observer
	8. What solar system bodies endanger Earth's biosphere, and what mechanisms shield it?	
	9. Can understanding the roles of physics, chemistry, geology, and dynamics in driving planetary atmospheres and climates lead to a better understanding of climate change on Earth?	Ice Giants mission, Saturn Probe, Titan mission , Io Observer, KBO mission
	10. How have the myriad chemical and physical processes that shaped the solar system operated, interacted, and evolved over time?	All missions

The Outer Solar System in Vision and Voyages

- Missions in development (JUICE and Europa Clipper) not included
- New mission concepts (not in V&V) in green

Several takeaways:

- Eight of ten priority questions are addressed via missions to the outer solar system.
- An Ice Giants mission appears for eight of the priority questions.
- Multiple Ocean Worlds missions (including Titan missions for #3 and #9) appear for seven of the priority questions.
- Io Observer and Saturn Probes appear for five of the priority questions

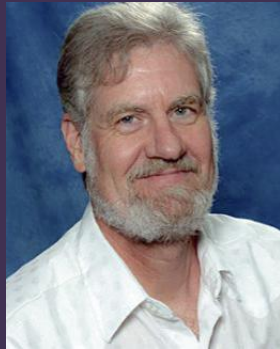
OPAG Draft Recommendations

- For **Flagship-class missions**, our top recommendation is to complete Europa Clipper.
 - Our top recommendation for a new start is an **Ice Giant Systems** mission.
 - Flying to either ice giant is scientifically compelling, but Neptune is preferred since Triton is a higher-priority Ocean Worlds target than Ariel or the other Uranian satellites
- Our second Flagship priority is a mission to search for life on an ocean world, most likely Europa or Enceladus.
 - We believe that the Europa Clipper mission will be essential to determine the best way to proceed at Europa, and that life detection technology development could prove essential.
 - Recommend that NASA study an Enceladus life-search mission.
 - Recommend that the next Decadal Survey include a Priority Question about actual life detection rather than just the study of habitability.
- For **New Frontiers** class missions, OPAG supports opening competition to all solar system destinations, as recommended by the National Academies in 2008.
 - In particular, we support the inclusion of Enceladus and Titan ocean worlds missions along with Io Observer and Saturn probes. Other concepts deserve consideration as well, such as a mission to KBO planets. All of these concepts would benefit from pre-decadal studies.
- For Discovery class missions, we strongly support efforts that open up the outer solar system to Discovery, such as allowing radioisotope power systems (RPS) to be proposed, and development of more efficient power sources
- Smallsat missions are feasible as add-ons to larger missions to outer planets, and we support continued study and technology development for such concepts, leading to actual flight opportunities.

Summary Recommendations

Europa Clipper	Continue development towards arrival in 2020s.	
New Flagship-class missions	Ice Giants system	Life search in ocean world
New Frontiers missions	Io, Saturn, Enceladus, Titan, KBO planets (not prioritized)	As open as possible to possible destinations.
Discovery missions	Allow RPS	Advance technologies to enable outer planet missions
Smallsat missions	Continued studies	Actual flights as riders to larger missions.
Telescopic observations	Dedicated space telescope	Other opportunities
R&A	As needed to support top-priority missions and a healthy research community	
Technology	As needed to support top-priority missions	

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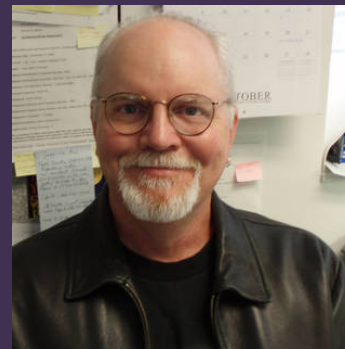
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