

Scientific Goals for Exploration of the Outer Solar System

*Explore Outer Planet Systems and
Ocean Worlds*

**OPAG Report
v. 28 August 2019**

**This is a living document and new revisions will be posted
with the appropriate date stamp.**

Outline

August 2019 Letter of Response to Dr. Glaze Request for Pre Decadal Big Questions.....i, ii

EXECUTIVE SUMMARY.....	3
1.0 INTRODUCTION	4
1.1 The Outer Solar System in Vision and Voyages	5
1.2 New Emphasis since the Decadal Survey: Exploring Ocean Worlds.....	8
2.0 GIANT PLANETS	9
2.1 Jupiter and Saturn	11
2.2 Uranus and Neptune	15
3.0 GIANT PLANET MAGNETOSPHERES	18
4.0 GIANT PLANET RING SYSTEMS.....	22
5.0 GIANT PLANETS’ MOONS	25
5.1 Pristine/Primitive (Less Evolved?) Satellites’ Objectives	26
5.2 Ganymede Science Objectives	31
5.3 Europa Science Objectives.....	35
5.4 Io Science Objectives.....	40
5.5 Enceladus Science Objectives	44
5.6 Titan Science Objectives.....	47
5.6 Triton Science Objectives	50
6.0 PLANETS IN THE KUIPER BELT	53
7.0 OCEAN WORLDS AND THE SEARCH FOR LIFE	58
7.1 Ocean Worlds: Understanding Oceans and Habitability	58
7.2 The Search for Life in Ocean Worlds	61
8.0 OPAG RELEVANCE BEYOND THE OUTER SOLAR SYSTEM	64
9.0 TECHNOLOGY	65
10.0 TELESCOPIC OBSERVATIONS	72
11.0 WORKFORCE ISSUES	74
12.0 SUMMARY RECOMMENDATIONS	76
Key References	78
OPAG Steering Committee	79

Dear Dr. Glaze,

In response to your recent request, here we provide a list of “Big Questions” as developed by the OPAG community. The OPAG community drew from its Scientific Goals documents, the Roadmap to Ocean Worlds, previous Planetary Science Decadal Surveys, Europa Lander and Ice Giant System mission concept studies, and community discussion at the 20-21 August 2019 OPAG meeting. The resulting ideas were combined and curated by the OPAG Steering Committee to produce a final set of three “Big Questions” and one planetary-science-wide, cross-divisional theme.

You also requested big science questions the OPAG community perceives to be of importance for the other AG communities. We believe that our three Big Questions are also responsive to your second request, as our community discussion strived to formulate the most fundamental questions that encompass all of planetary science relevant to all of the AGs.

These “Big Questions” are listed below along with example bulleted, high-level, OPAG-specific sub-questions:

Big Question #1: What is the distribution and history of life in the solar system?

- Does life or do habitable conditions exist beyond the Earth?
- What controls the habitability of ocean worlds?
- Do ocean worlds host life now, or did they in the past?
- What is the potential for prebiotic chemistry in ocean worlds, and how far towards life has this progressed?
- What role did the giant planets play in the emergence of life on Earth or elsewhere in the solar system?

Big Question #2: What is the origin, evolution, and structure of planetary systems?

- What was the initial chemical profile of the protoplanetary disk as informed by noble gas content in the giant planets, and how did this profile impact the overall formation and evolution of our solar system?
- What are the possible architectures of planetary systems, and how do these different configurations affect planet formation and evolution (e.g., giant planet migration, tidal evolution, etc.)?
- What controls the formation, evolution and internal structures of gas giants, ice giants, planetary satellites (particularly ocean worlds), rings, and small bodies in the outer solar system?
- How do planetary crusts/cryospheres, oceans, atmospheres, and magnetospheres form and evolve in the outer solar system, and how do they influence the evolution of bodies in those systems?

Big Question #3: What present-day processes shape planetary systems, and how do these processes create diverse outcomes within and across different worlds?

- How do the chemical and physical processes in the solar system scale between planet size and location within the solar system?

- What is the dynamic relationship between the planets, rings, and moons of giant planet systems, and how do these relationships influence their constituent members?
- How do the magnetospheres of gas and ice giants influence the dynamics, composition and structure of the atmospheres, rings, and moon surfaces?
- How do the aurorae and induced magnetic fields of ocean worlds characterize the coupling between planets, moons, and magnetospheres?
- What are the mechanisms, drivers, and rates for transporting heat and materials within, and ejecting them from, (cryo-)volcanically active worlds?
- How does coupled orbital evolution and tidal heating affect the interior structures and activity of satellites, and how does the interior evolution of the primaries affect this evolution (e.g., resonance locking)?
- What drives the transport of energy and materials within the deep interior of the giant planets?
- How do the atmospheric dynamics, cloud microphysics, radiative transfer, and chemistry interact to form stable and transient features observed in outer planet and satellite atmospheres?
- How do the ice giant magnetospheres and atmospheres respond to the impulsive solar wind forcing created by their unusual geometries, and what effect does solar insolation play on weather and upper atmospheric structure?

Cross-Divisional Theme: How can knowledge of the solar system advance our understanding of the Earth, Sun, and Exoplanets?

- How does knowledge gleaned from studying the outer solar system make us better stewards of our own planet?
- How does the study of our planet inform our understanding of the outer planets and their moons?
- How do studies of the diverse present-day oceans in the solar system advance biological, chemical and physical oceanography?
- How does the study of the solar wind interaction at bodies in the outer solar system improve our understanding of the Sun and the propagation and evolution of its dynamic atmosphere?
- How can solar system bodies inform our understanding of bodies in exoplanetary systems?

Lastly, the OPAG community also discussed the critical importance of equity, diversity, and inclusion in formulating the statement of task for the Decadal Survey and in the composition of the Survey leadership (especially in the chair(s) and steering committee). OPAG suggests that the statement include language such as the following:

“The composition of the Decadal Survey panels - particularly the Chairs and Steering Committee - should take full advantage of the diversity of the planetary science community in factors such as area of expertise, gender, race, ethnicity, career stage, types and sizes of institutions, geographic distribution, and disability status.”

We note that Astro2020 has two co-chairs, rather than a chair and a vice-chair; many members of OPAG believe this would be a good approach for the Planetary Decadal Survey as well, particularly given the wide range in topics and targets covered.

Please let us know if you have any questions or would like any clarification.

Jeff Moore and Kunio Sayanagi for the OPAG Steering Committee
August 27, 2019

EXECUTIVE SUMMARY

This document describes the science objectives for exploration of the outer solar system. It is 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. This document will be used as a resource for defining technology development directions and needed laboratory experiments, modeling, and other research. It should be used as a resource for mission and instrument science objectives. Ultimately this document will guide our preparation for the outer solar system portion of the next decadal survey, including mission studies being done in preparation for that survey.

Exploration of the outer solar system uniquely addresses NASA’s top-level strategic goal (2018 NASA Strategic Plan) to understand the Sun, Earth, solar system, and universe, including answering fundamental scientific questions and searching for life elsewhere. The 2018 NASA authorization act from Congress now includes “the search for life’s origins, evolution, distribution, and future in the universe”. The outer solar system contains many unexplored bodies and environments. It contains critical evidence for how our solar system formed, and it hosts environments where physical processes can be observed today which were central to formation of the earliest planetesimals and which may have been acting on early Earth. The outer solar system is also where extensive liquid water oceans exist today, potentially the home of complex life forms.

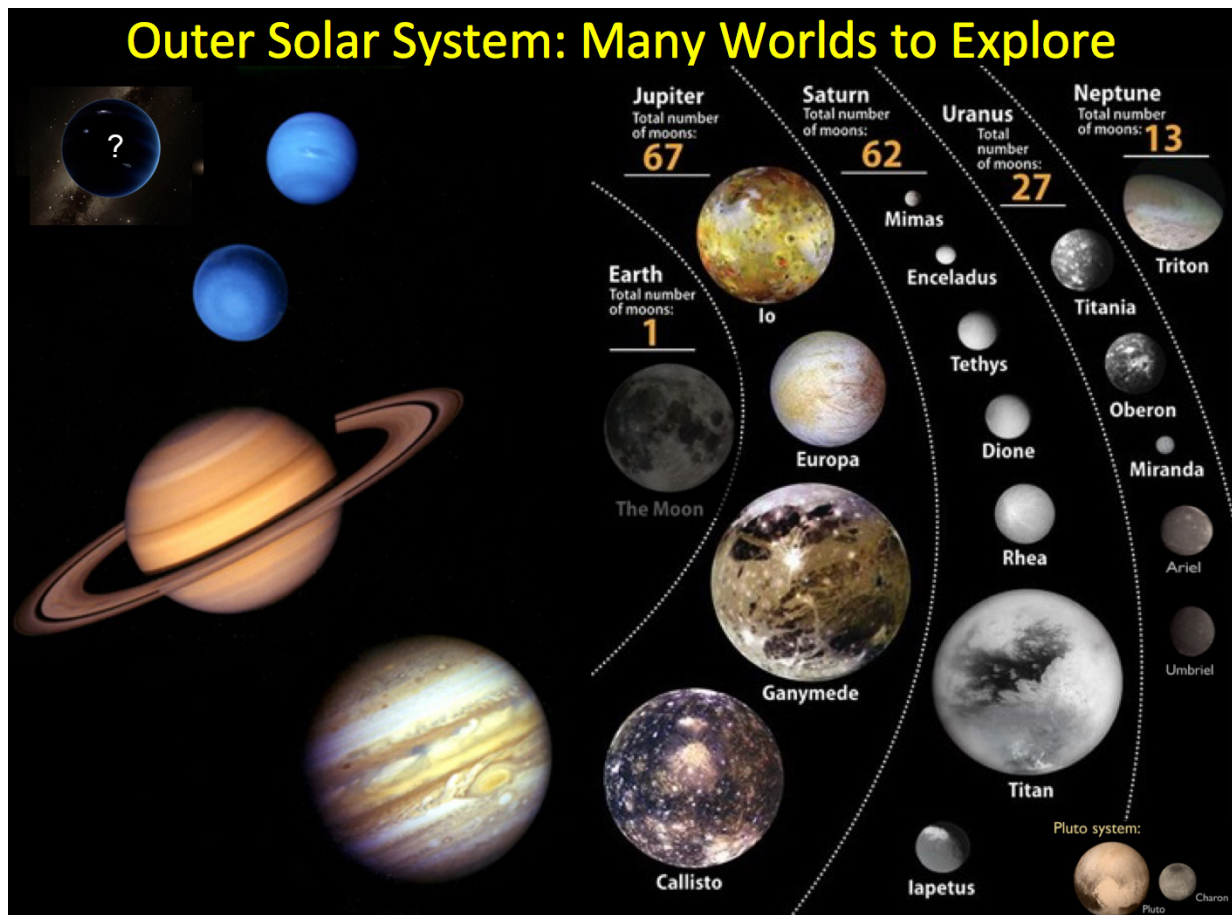
The emphasis for future exploration of the outer solar system is to understand giant planet systems and ocean worlds.

The tremendous diversity of bodies in the outer solar system provides the opportunity for a wide variety of scientific investigations. The giant planets provide insight into solar system formation through studies of their atmospheric composition and internal structure. The satellites of the giant planets, some comparable in size to terrestrial planets, and the dwarf planets of the Kuiper Belt (“KBO planets” hereafter) offer opportunities to study extreme environments on worlds that have experienced very different histories. Tidal heating of satellites leads to current activity and conditions potentially favorable to habitability. The rings and magnetospheres of the giant planets illustrate currently active processes (of collisions and momentum transfer) that played important roles in early stages of solar system formation. The volcanism of Io and atmosphere of Titan inform important processes on the terrestrial planets and exoplanets. The outer planets feature prominently in molding the solar system in a complex endgame that appears to involve orbital migration of the giant planets, scattering planetesimals into the inner solar system, and delivering water and other life-critical materials to the terrestrial planets.

One of the primary opportunities in the outer solar system is the chance to explore subsurface oceans. The outer solar system is replete with ocean worlds including Europa, Ganymede, Callisto, Enceladus, Titan, and probably Triton and others. In the inner Solar System only Earth has an ocean today, and oceans may be key to understanding the origin(s) and evolution of life. The ocean worlds may be the best places to search for extant life beyond Earth.

Two major planetary systems in our solar system have never had a dedicated spacecraft mission: the ice giants Uranus and Neptune. Voyager 2 flew through each system and gave a scouting report: these are exciting planetary systems. Given their importance to understanding planetary formation and evolution, exoplanets, and potential ocean worlds, as well as the unique environments on display there, exploration of ice giants was a top recommendation in Vision and Voyages. While Uranus and Neptune are each a compelling scientific target, they also have critical differences and each has different things to teach us. Ultimately both must be explored if we are to understand ice giants as a class of planet.

OPAG strongly endorses continued Earth-based research into all bodies of the outer solar system, and development of the technology that enables us to fly there and operate. Attempts to actually detect extant extra-terrestrial life should become a NASA objective in the next decade. We strongly support the continued development and launch in the early 2020's of the Europa Clipper mission to begin our first detailed study of an ocean world beyond Earth. As the highest priority new "flagship" (or "large directed") mission we strongly endorse a comprehensive ice giant system 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. OPAG also strongly supports current pre-project development efforts towards a potential Europa lander, and notes that that these efforts would benefit lander technology developments targeting other Ocean Worlds. Beyond the Europa and Ice Giant missions, we encourage a science-driven, cost-effective progression of small and large missions into this rich and diverse region.



1.0 INTRODUCTION

1.1 The Outer Solar System in Vision and Voyages

The Decadal survey for 2012-2023, Vision and Voyages (V&V hereafter) places a high priority on the outer solar system both in priority science questions and in recommended missions. **OPAG science priorities are currently identical to those in V&V, including all three of the crosscutting themes and eight of the ten priority questions** (the other two are not relevant to the outer solar system). OPAG may consider recommending new science priorities to the next Decadal Survey, but has not begun that process, with one exception. We strongly recommend that the next Decadal Survey include a Priority Question about actual life or biosignature detection rather than just the study of habitability.

Table S.1 of V&V described science themes, priority questions, and candidate missions. In Table 1 below we repeat the themes and questions, along with an updated list of candidate missions (in green) to the outer solar system (not including Europa Clipper and JUICE, already in development). Note that Table 1 simply lists “multiple Ocean Worlds missions” as a placeholder for multiple new concepts in development, including Europa Lander, and various mission concepts to Enceladus, Titan, and elsewhere.

Table 1: V&V Crosscutting Science Themes and Priority Questions, and candidate missions relevant to OPAG

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, KBO 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

Several takeaway points from Table 1 are:

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

The mission priorities in V&V mirror their relevance to the key questions. Accordingly, relevant to OPAG, V&V ranked a Uranus Orbiter and Probe mission (i.e. an Ice Giants mission) as a high priority to initiate in the decade *even in a reduced-funding scenario*. Since the decadal mid-term report in 2018 called for additional study of an Ice Giant mission instead of implementation, such a mission now seems highly unlikely to start before 2023. However, the optimal launch window for a Neptune Orbiter is from 2029-2030 so a new start before 2023 may be needed. **OPAG reiterates that such a mission represents an extremely high priority.**

V&V listed a descoped Jupiter Europa Orbiter as a top priority, and that is now in development in the form of Europa Clipper. Other known Ocean Worlds such as Enceladus and Titan did not have any recommended mission opportunities in V&V (except Enceladus Orbiter as one of two options in the enhanced budget scenario), but NASA has chosen to include them in New Frontiers 4 (NF-4), and the Titan mission *Dragonfly* was selected for a Phase A study. NASA is also studying a Europa Lander mission, with a Science Definition Team (SDT) report released in 2017, although not considered in V&V. These actions show that NASA has a new interest in exploring Ocean Worlds, which is strongly supported by OPAG. OPAG initiated the Roadmaps to Ocean Worlds (ROW) study (<https://www.lpi.usra.edu/opag/ROW/>), which has a major impact on this OPAG goals document.

V&V included Saturn Probes as a candidate for NF-4, while Io Observer was deferred to NF-5. The decadal mid-term review recommended that NF-5 be initiated by December 2021, which OPAG strongly supports. As discussed in Section 2, atmospheric probes remain a high priority for measuring key isotopic ratios and Noble gas abundances on Saturn (and the Ice Giants). Note also that we listed Io Observer and a Titan mission for Q3 (Table 1) about evolution of inner planets, although not listed for Q3 in Table S.1 of V&V. That is because the extremely high-volume volcanism and outgassing key to the evolution of all of the terrestrial planets can be directly observed (within our solar system) only at Io, and because Titan's nitrogen and CH₄-rich atmosphere informs us about the early evolution of Earth's atmosphere and perhaps that of Mars. See section 8 more for about how outer solar system studies impact our understanding of worlds in the inner solar system and exoplanets.

How does OPAG prioritize future missions? Our goal is to represent the consensus view of the entire outer planets science community supported by NASA. An Ice Giants mission is the clear consensus priority because it addresses the full range of planetary science (atmospheres, magnetospheres, rings, and satellites including candidate Ocean Worlds) and is especially important to the study of exoplanets. Uranus and Neptune are the only large planets to which there has never been a dedicated spacecraft mission. The ROW priorities document favors Neptune over Uranus because Triton may be a stronger candidate for an ocean world than any mid-sized Uranian moon, although the wide diversity of the Uranian moons, some of which could have been or still be ocean worlds (and the relatively young surfaces of some), is compelling. Eventually, both of these planetary systems need to be explored, as there are major differences between them. We strongly support the new emphasis on Ocean Worlds, because these are the best places in the solar system to search for extant life beyond Earth. A landed mission to an ocean world would provide excellent, cross-cutting science for a large portion of the OPAG community including geophysics, chemistry, habitability/biosignature detections, current activity, cryovolcanism, ocean dynamics, radiation and more. OPAG also continues to support science objectives that are not directly tied to Ocean Worlds, and advocates for all types of outer solar system exploration in New Frontiers, Discovery, or other opportunities.

There have been many fundamental new results regarding the outer solar system and ocean worlds since V&V was finalized; some of these are listed in Table 2.

Table 2. Top New Outer Planet Science Results Since Vision and Voyages (V&V)

Result	References
Cassini discovery of subsurface water ocean in Titan	less 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	Freikh and Murray-Clay, <i>Astron. Jour.</i> 154, 2017; Lambrechts and Lega, <i>A&A</i> 606, 2017
Competing explanations for Uranus' anomalously low internal heat flux	Nettelmann et al., <i>Planetary and Space Science</i> 77, 2013; Kurosaki and Ikoma, <i>Astron. Jour.</i> 153, 2017
Dynamic coupling of dynamos and zonal winds in Uranus and Neptune	Soderlund et al., <i>Icarus</i> 224, 2013
Daily reconnection of Uranus' magnetosphere during summer and winter solstice	Cao and Paty, <i>JGR Space Physics</i> 2017
Hydrothermal water-rock interactions in Enceladus' ocean	Hsu et al., <i>Nature</i> 519, 2015
Enceladus' plume dynamics and implications for origin and transport through the ice shell	Nakajima and Ingersoll, <i>Icarus</i> 272, 2016; Ingersoll and Nakajima, <i>Icarus</i> 272, 2016; Tucker et al., <i>Icarus</i> 257, 2015; Ingersoll and Ewald, 2017, <i>Icarus</i> 282.
Composition and bathymetry of Titan seas	Mastrogiuseppe et al., <i>GRL</i> 41, 2015; Mitchell et al., <i>GRL</i> 42, 2015; Le Gall et al., <i>JGR</i> 121, 2016; Hayes et al., <i>Ann. Rev. Planet. Sci.</i> 44, 2016
Understanding Titan's atmospheric circulation, methane cycle, atmosphere-surface interaction, and composition	Mitchell and Lora, <i>Ann. Rev. Earth Planet. Sci.</i> 44, 2016; Newman et al., <i>Icarus</i> 267, 2016; Charnay et al., <i>Nat. Geos.</i> 8, 2015; de Kok et al., <i>Nature</i> 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., <i>Ap. J. Lett.</i> 840, 2017
Evidence of a plume on Europa from Galileo magnetic and plasma wave signatures	Jia, X., et al., <i>Nature Astronomy</i> 2, 2018.
Macromolecular organic compounds from the depths of Enceladus	Postberg, <i>et al.</i> , <i>Nature</i> , 558 , 564–568, 2018.

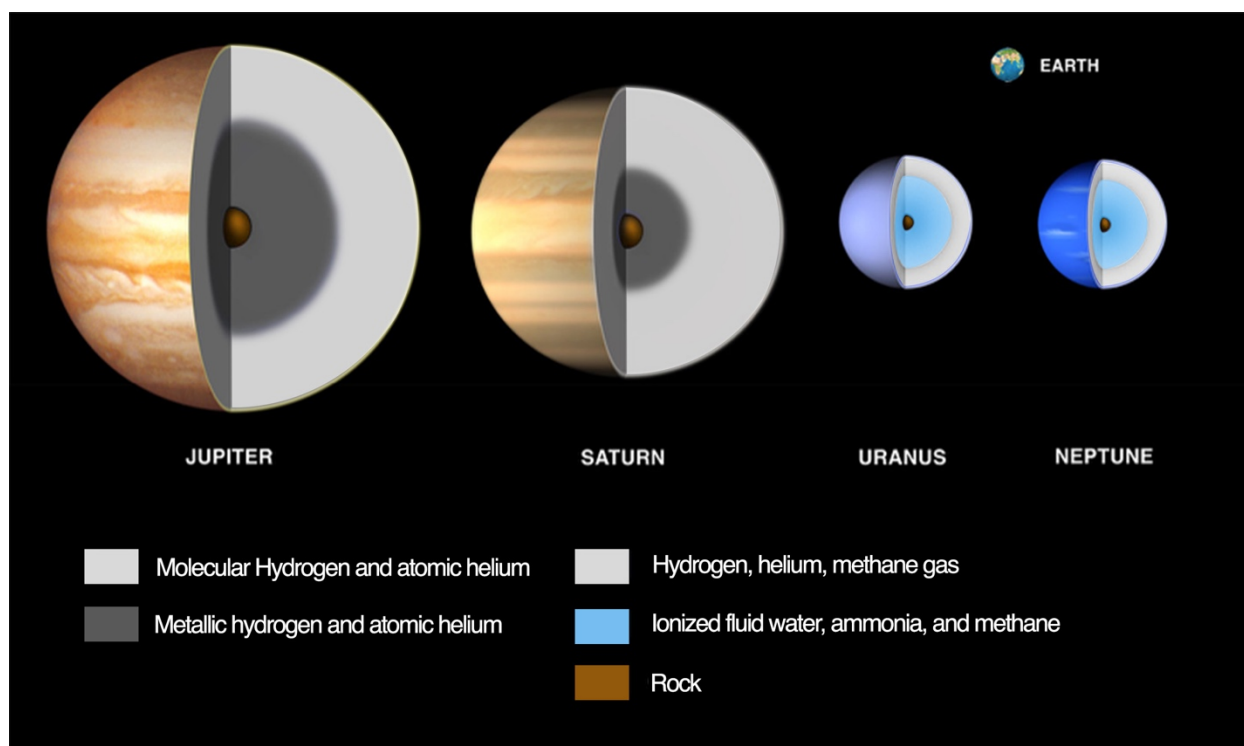
1.2 New Emphasis since the Decadal Survey: Exploring Ocean Worlds

Liquid water is essential to the existence of life on planet Earth. Water is found in abundance in the outer solar system, from the ice giant water worlds of Uranus and Neptune (although under high pressure) to the moons of Jupiter and Saturn and perhaps moons of the ice giants and KBO planets such as Pluto. One of the most surprising revelations of the last decade is the number of moons that are likely to have large internal bodies of water – global “oceans” – under their icy crusts. Since V&V was finalized, Cassini has confirmed oceans in Enceladus and Titan (and maybe Dione and Mimas), New Horizons results are consistent with an ocean in Pluto, and Dawn results suggest a past ocean in Ceres, with possible present-day subsurface pockets of liquid. New analyses have also strengthened the case for oceans in Ganymede and Triton (Table 2).

The 2016 Congressional Commerce, Justice, Science, and Related Agencies Appropriations Bill (hereafter CJS) directed NASA to create an Ocean Worlds Exploration program to seek out and discover extant life in habitable worlds in the Solar System. In support of these efforts, OPAG, with cooperation from NASA's Planetary Science Division, formed the Roadmaps to Ocean Worlds (ROW) group to assemble the scientific framework guiding the exploration of Ocean Worlds, which can serve as input to the next Decadal Survey. The topic of Ocean Worlds is rich, and the ROW group has consolidated and prioritized critical science questions which are summarized in Section 7.0 and in their full report (<https://www.lpi.usra.edu/opag/ROW/>).

2.0 GIANT PLANETS

Giant planets in our solar system come in two distinct flavors. Jupiter and Saturn are gas giants, with ~85% of their mass made up of hydrogen and helium. Uranus and Neptune are ice giants, with about 65% of their mass thought to be water, 25% rock, and only 10% H₂ and He gas. The highest-level goals and objectives are the same for studying both types of giant planets, but we differentiate between gas and ice giants when discussing most details. After the wealth of scientific results that have been returned by Galileo and Juno in the Jupiter system and Cassini in Saturn's, the outer planets community finds the Uranus and/or Neptune system to be the next fertile target for exploration. Since the release of *Vision* and *Voyages*, ice giant science goals have been studied at two international conferences and in one NASA mission study. Their conclusions are consistent with V&V, and have been used as inputs to this document.



The composition and structure of the gas giants (Jupiter and Saturn) are much different than those of the ice giants (Uranus and Neptune). Simplified three-layer models are shown above which neglect some of the complexities known to exist.

The giant planets have played a critical role in shaping our solar system. Current theory suggests their formation and migration had profound influences on the location and composition of the terrestrial planets, asteroids, and comets. The giant planets also hold clues to conditions in the proto-planetary nebula and the planetary formation process. These clues lie not only in their composition and internal structure, but also in the physical processes that occur within their unique environments. Looking beyond our solar system, we have found that giant planets are ubiquitous in exoplanetary systems. By coupling the "ground truth" of the giants in our system with what we see around other stars, the coming years will revolutionize our understanding of the evolution of planetary systems.

This section (Section 2.0) discusses the deep interiors and neutral atmospheres of the giant planets. Their ionospheres and magnetospheres are discussed in Section 3.0, rings in 4.0, and moons in 5.0 and 7.0. While divided up for convenience of discussion, it is critical to examine the interactions between these components. Even though they are physically distinct, components interact through electromagnetic and gravity forces, as well as direct exchange of materials and associated chemical reactions. Some processes can be observed remotely, while others can be measured only in-situ; thus, multiple measurement approaches must be considered to gain a comprehensive understanding of each of the giant planet *systems* as a whole.

We identify three overarching goals in the study of the four giant planets in our solar system:

Goal 1: Explore giant planet processes and properties

Explore the processes and properties that influence giant planets in our solar system (including origin/formation/evolution, orbital evolution, composition, structure, and chemical, dynamical and other environmental processes). Goal 1 can be further categorized into the following 4 subgoals;

- a. Characterize present-day state
- b. Examine temporal evolution
- c. Understand processes that shape and maintain the mean state, and drive temporal evolution
- d. Determine the origin and past temporal evolution, and predict the future.

Goal 2: Use giant planets to further our understanding of other planets and extrasolar planetary systems

Investigate observable processes and activities ongoing in our giant planet systems as an aid to understanding similar processes and activities on Earth, other planets and in other planetary systems. As the processes observable in the solar system planets are often difficult or nearly impossible to detect on their extrasolar counterparts, investigation of the local planets provides essential insights for the distant worlds.

Goal 3: Determine giant planets' influences on habitability

Test the hypothesis that the existence and location of the giant planets in our solar system has contributed directly to the evolution of terrestrial planets in the habitable zone. (The possibility of habitable environments being created within giant planet satellites is discussed in the "Giant Planets' Moons" and "Ocean Worlds" sections of this document.)

An important lesson that has been learned about the giant-planet systems is that they are highly dynamic and evolve on various temporal and spatial scales. Some of the time-scales are too long for flyby or even orbiting spacecraft, making a dedicated planetary space telescope useful (see Section 10). Examining the temporal evolution of these planets often lead to discoveries of new processes that operate in these systems. The four giant planets harbor common processes, and yet their outcomes are different; the ultimate goals of giant-planet science are to understand what differentiated these worlds, use the differences to reveal the origin and evolution of our solar system, and apply the results to other planetary systems.

Below, the deep interior and neutral atmosphere is discussed for Jupiter and Saturn first, and then Uranus and Neptune. Other aspects of these planetary systems are discussed in later sections.

2.1 Jupiter And Saturn

1. What is the interior structure and bulk composition of the gas giants (including noble gas abundances and the isotopic ratios of H, C, N, and O)?

Knowledge of giant planets' bulk composition and interior structure (e.g. degree of internal differentiation) are key for understanding their formation and evolution. The properties of the deep interior are also a crucial boundary condition for the heat flow, composition, and dynamical processes acting in the observable atmosphere.

Regarding bulk composition, the abundance and isotopic ratio of noble gas and elements that form the volatile species (H, C, N and O) inform us about the formation and evolution history of the outer solar system. For Jupiter, even though the Galileo probe has answered some of our compositional questions, key gaps remain. The ratios of noble gases in Jupiter point to an extremely low formation temperature for the icy planetesimals that were incorporated into the planet (consistent with what is measured in most comets), while the $^{14}\text{N}/^{15}\text{N}$ ratio measured is consistent with N_2 (and not NH_3) being the source species for most of Jupiter's atmospheric nitrogen. Several planetary formation models can explain these measurements, but make differing predictions for Saturn. Therefore, it remains of great interest to measure the noble gas and isotopic ratios on Saturn (measurements which require an atmospheric probe). Strong enhancements in noble gas abundances for non-radiogenic components that are preferentially trapped in cold ices below 40 K (e.g., neon and argon), or unexpectedly large isotopic ratios (e.g. $^{15}\text{N}/^{14}\text{N}$), could be a key indicator of planetary migration from the cold outer solar system. Another important species to measure is water, whose abundance remains unknown on Jupiter and Saturn (though the Juno mission is expected to constrain it at Jupiter).

The interior structures of both Jupiter and Saturn are unknown in many key respects: the presence and size of a discrete rocky core; the extent and properties of metallic hydrogen; and whether or not there is evidence of core erosion. The Juno mission is expected to provide constraints on these features at Jupiter, and analysis of the Cassini end-of-mission data may do the same at Saturn. Measuring the normal mode oscillation of Jupiter and Saturn should provide revolutionary new insight on the interior density structure – the approach is also known as giant planet seismology. A recent discovery revealed that fine-scale structures in Saturn's rings record the normal modes of the planet, and provide insight into the deep interior. For the other planets with less extensive rings, direct observation of the planet may be the only method to measure the normal modes. As of this writing, direct observation of the normal modes (perhaps using a Doppler imager) remains a challenging objective that promises worthy return. A ground-based detection of Jupiter's oscillations has been reported, but not yet confirmed.

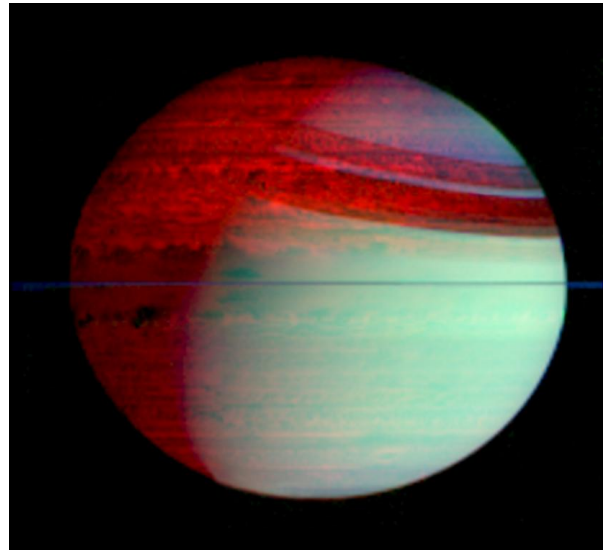
Another observable that provides valuable insight on the giant planet interiors is the structure of the magnetic field, which is generated by the dynamo processes in the electrically conductive region deep inside the planets. This topic is discussed in more detail in the Magnetic Fields section (§3.0) of this document.

[Q1, Q2, Q3 in V&V; see Table 1]

2. What are the sources of internal heat, the nature of heat flow, and the radiation balance in gas giants?

Planets form hot, and generally cool over time. Radiation to space is the ultimate heat loss mechanism, modulated by the ability of the interior and atmosphere to transport heat out to the radiative zone, and by secondary internal heating processes (e.g. radiogenic, helium rain).

The origin of the majority of the internal heat is the gravitational contraction that converts the gravitational potential energy to thermal energy. The release of gravitational potential energy continues to this day; however, its details remain unknown. For example, for Saturn, the internal heat release may be dominated by droplets of Helium falling toward the planet's center, called *Helium rain*. Answering whether the Helium rain provides a significant energy source involves understanding the properties of a hydrogen-helium mixture under high temperature and pressure, and can provide important insight on the thermal evolution of Saturn and other planets. Deep internal convection also modulates dynamo activity in the conducting layer, as discussed in Section 3.0.



The internal energy flux should also have an impact on the observed cloud layers and atmosphere. For example, episodic storms like Saturn's quasi-30-year cycle "Great White Spots" may be driven by internal heat flux. Probing the origin of these storms will require knowledge of the thermal structure of the atmosphere (in particular whether a non-adiabatic thermal stratification exists) below the clouds, perhaps to the 1000-bar pressure level. The role of moist convection in shaping the thermal structure also remains unknown. Above the cloud layers, vertically propagating atmospheric waves may play a major role in the energy balance, and may contribute to the unexpectedly warm thermospheres of the giant planets.

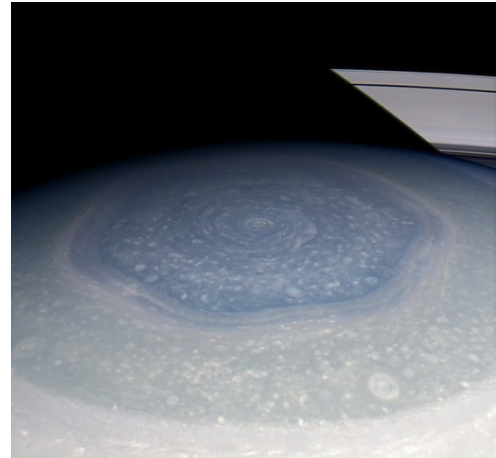
All these energy-related processes are fundamentally important to the evolution and current structure of giant planets, influencing the temperature profile, the chemistry, and the dynamics throughout the planet. Linkages of these processes to extrasolar giant planets should also be examined; for example, comparing the radiative balance of solar system giant planets to the many "hot Jupiters" that orbit closely around other stars that exhibit large radii should lead to further understanding of the interior heat transport/release mechanisms that maintain the energy balance.

[Q7, Q9, Q10]

3. What is the vertical and horizontal structure of the global circulation and what dynamical processes force and maintain the circulation in gas giant atmospheres? What

seasonal/temporal changes occur and why? Do various forcing mechanisms maintain the atmosphere in equilibrium, oscillating about an equilibrium, or evolving in steady-state?

The gas giants in our solar system have strong zonal winds that exhibit various spatial and temporal oscillations (e.g., Saturn's Hexagonal jet around the north pole, Saturn's "Ribbon" jet at 45°N, Jupiter's equatorial Quasi-Quadrennial Oscillation, Saturn's equatorial Semi-Annual Oscillation), long-lived discrete atmospheric features (e.g. Jupiter's Great Red Spot, Saturn's Polar vortices), as well as short-lived weather features (storms). Detailed measurements of the gravity fields by the Juno and Cassini missions are expected to provide new information on the depth to which these observed cloud-top wind structures extend.



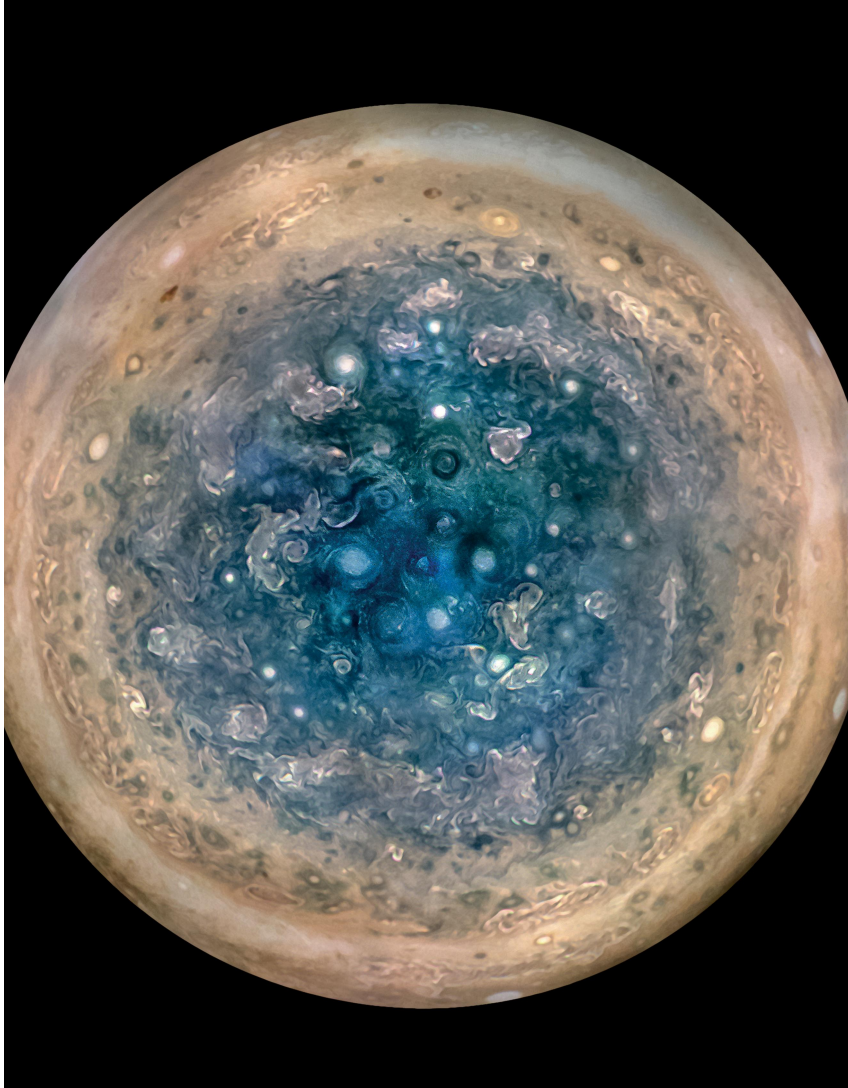
In spite of these observations, however, the underlying dynamical processes and energy transport are not understood. For example, the abundance and distribution of certain species (e.g. hydrocarbons, NH_3 , H_2S , and the H_2 ortho-para ratio) is indicative of meridional, longitudinal, and vertical circulation patterns, but why the observed patterns exist, and how they are linked to the visible cloud bands are still unknown (**Jupiter's NH_3 distribution observed by the microwave radiometers carried by the Juno spacecraft being an example**). We have also seen seasonal changes and longer term quasi-periodic variations on Jupiter and Saturn for which theories exist, but there are not yet discriminating observations (Saturn's most recent "Great Storm" being a prime example of a quasi-periodic, planetary-scale outburst).

[Q7, Q9, Q10]

4. What is the composition of gas giant atmospheres, and what are the photo- and thermo-chemical processes acting within those atmospheres (including cloud processes)?

Understanding the composition and chemistry of gas giant atmospheres is necessary for understanding the current state of these planets, and provides clues about their formation and evolution. For example, non-equilibrium species seen in the upper troposphere, such as PH_3 , as well as the ortho-para hydrogen ratios are a sign of vigorous vertical transport and hold clues to the bulk composition of the interior. Spatial and temporal variations in condensable species are a tracer of atmospheric dynamics and indicator of cloud formation.

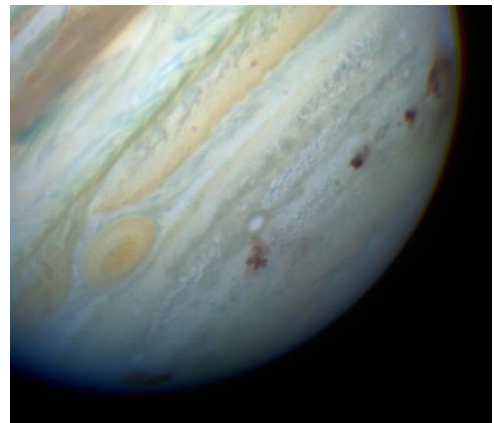
[Q1, Q2, Q7, Q9, Q10]



Cloud features and storms seen at Jupiter's South Pole by the Juno spacecraft.

5. What was and is the role of gas giant planets in creating/mitigating impact events throughout the solar system?

Jupiter may play the role of protector of the inner solar system, minimizing the number of large, disruptive impacts later in our solar system's history including today (the many impacts seen on Jupiter yield stark evidence of this ongoing activity). Conversely, as discussed below, migration of the ice giants early in our solar system's history may be responsible for the late heavy bombardment in the inner solar system. Both these mechanisms are important factors in understanding the composition of the terrestrial planets and the emergence and subsequent evolution of life. Measurements of the



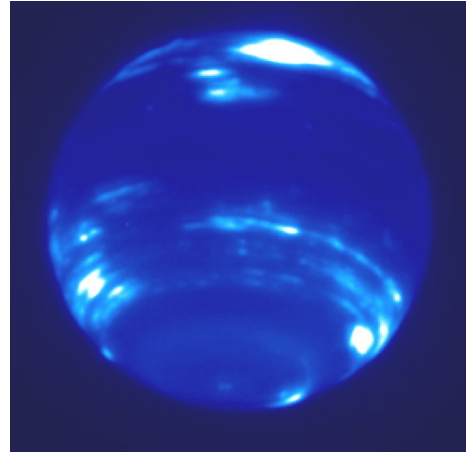
present-day impact rate would also provide valuable insights on the small-body population in the outer solar system today, and on the continuing influence of Jupiter in the evolution of the outer solar system.

[Q1, Q2, Q3, Q4, Q10]

2.2 Uranus And Neptune

1. What is the interior structure and bulk composition of the ice giant planets (including noble gas abundances and the isotopic ratios of H, C, N, and O)?

As with gas giants, knowledge of the fundamental properties of ice giants is key for understanding their formation and evolution. In particular, the abundances of various ices, the noble gases, and certain isotopes are diagnostic of competing formation theories, and may also provide evidence of radial migration of planets and planetesimals in forming planetary systems. The properties of the deep interior are also a crucial boundary condition for heat flow, composition, and dynamical processes acting in the observable atmosphere. These aspects are surely different for the Uranus system (with essentially no detectable heat flow) and the Neptune system (with the largest internal heat flow relative to absorbed sunlight of any giant planet in our Solar System), as discussed in the next question.



Some of the key questions about the interior structures of Uranus and Neptune are: What are the sizes of their rocky cores? How differentiated are they? How do the two planets differ? Do vast ionic oceans exist within both planets? Regarding composition, noble gas abundances and isotopic ratios are unknown or at best poorly constrained on both ice giants. There is also the lingering question as to whether the strong depletion of NH_3 in their atmospheres relative to solar abundances is a sign of unaccounted chemical processes deep in the planets or a bulk depletion in nitrogen compounds. Could any difference between Uranus and Neptune be explained by the giant impact hypothesized to have knocked Uranus' rotation axis on its side late in the formation process? A spacecraft flown to at least one of the ice giants is needed to address these questions, but unlike the gas giants, no such mission is currently on the books.

[Q1, Q2, Q3]

2. What are the sources of internal heat, the nature of heat flow, and the radiation balance in ice giants?

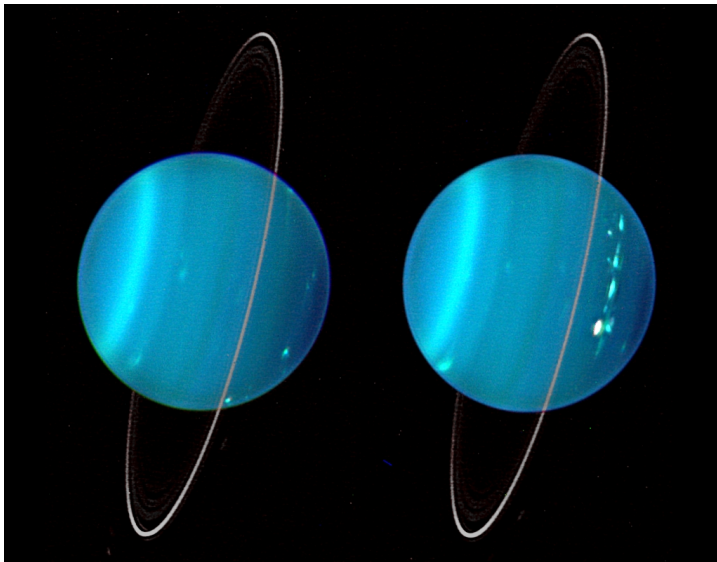
Is the low amount of internal energy being released by Uranus (an order of magnitude lower than released by Neptune) a sign of Uranus having cooled much faster (helped, perhaps, by the giant impact assumed to have knocked it on its side), is this a sign of heat being trapped in the interior by a lack of convective transport, or is it in a transient quiescent state? (In fact, it remains to be confirmed whether or not Uranus is releasing any internal heat, as the existing Voyager data allows zero as well as small values.) To what extent does Uranus' low internal energy release (which

increases the importance of sunlight as an atmospheric energy source) make it an analog for giant exoplanets extremely close to their host stars (so called "hot Jupiters" and "hot Neptunes" whose energy balance is presumed to also be dominated by stellar input)?

[Q7, Q9, Q10]

3. What is the global circulation and what are the dominant dynamical processes in ice-giant atmospheres? What seasonal/temporal changes occur and why?

Very little is known about the global atmospheric patterns and discrete features on the ice giants, and even less about their temporal variability. On both planets, tracking discrete cloud features has revealed global zonal system of wind patterns that have a retrograde peak at the equator, and prograde peak at the mid-latitude in each of the hemispheres; however, due to the dearth of trackable cloud features, no longitudinal variation in the wind has been revealed. Measurements of the cloud-top wind fields and wave propagation will inform us about the mechanisms that maintain the global circulation patterns, and should be a priority objective of future missions to these planets.



Observation of discrete atmospheric features have also remained difficult due to the challenges in obtaining images with high-enough resolution to resolve cloud features, and whether these planets harbor any long-lived feature is not known. A small number of discrete features have been recorded on the ice giant planets. On both planets, a dark anticyclonic vortex (and associated “Berg” and “Bright Companion” clouds) occasionally appears in the mid-latitudes, which tends to drift equatorward before they are dissipated – the formation mechanism of these dark spots remains

to be understood. A polar hotspot (presumably a cyclonic polar vortex) has been seen on Neptune (and was seen to split into two in 2007) but no localized vortex has been seen on Uranus. In addition, little has been learned about the spatial distribution and frequency of short-lived weather features (presumably convective storms). Temporal changes in the cloud bands and storm distributions on Uranus and Neptune have been clearly documented, however, the long orbital periods of those planets make it difficult to distinguish seasonal from stochastic processes.

The distribution of NH_3 and H_2S inferred from ground-based radio measurements indicates there is a stable, deep-seated circulation pattern creating pole-to-equator abundance gradients even deep in the troposphere, below the altitude of predicted cloud layers. This is reminiscent of, though much more extensive in latitude, than one recently discovered on Jupiter by the Juno mission. As on the gas giants, there is no dynamical model that successfully creates all the observed features. While there are many similarities between ice and gas giants, these planets also have clear

dynamical differences both between and within each class (e.g. Uranus appears to be less convectively active than Neptune). How all these dynamical features form and evolve is not clear (though there are intriguing hints that water condensation is important for convective processes), nor do we understand how or even if they are coupled to the deep interior or the uppermost atmosphere.

The above dynamical questions touch upon our objectives relating to internal heat and energy balance as well. Does Uranus' low internal heat release mean its atmospheric dynamics are dominated by solar inputs? Does that make it an analog, or at least a test-case, for models of the tropospheric dynamics of hot exoplanets close to their host stars?

[Q7, Q9, Q10]

4. What is the composition of ice giant atmospheres, and what are the photo- and thermo-chemical processes acting within those atmospheres (including cloud processes)?

The composition and chemistry of ice giant atmospheres provides clues about their formation, evolution, and current state. Spatial and temporal variations in condensable species are a tracer of atmospheric dynamics. A detailed understanding of chemical processes may allow us to recognize anomalies that could be: signs of migration of Uranus and Neptune; residue of the giant impactor thought to have struck Uranus late in its formation; or evidence for exogenic infall of materials in the outer solar system. A firm understanding of atmospheric chemistry is also necessary in order to infer interior processes and composition from atmospheric abundances.

[Q1, Q2, Q7, Q9, Q10]

5. What was and is the role of ice giant planets in creating/mitigating impact events throughout the solar system?

Migration of the ice giants early in our solar system's history may be responsible for the late heavy bombardment in the inner solar system, thought to have provided many of the volatiles (such as water) found on the terrestrial planets today. As discussed earlier, Jupiter may play the role of protector of the inner solar system, minimizing the number of large, disruptive impacts later in our solar system's history as well as today. Both these mechanisms are important factors in understanding the composition of the terrestrial planets and the emergence and subsequent evolution of life. Noble gas abundances (e.g. neon and argon) and isotopic ratios (e.g. $^{14}\text{N}/^{15}\text{N}$) can be tracers of the formation temperature—and hence location of formation—of giant planets in the early solar system.

[Q1, Q2, Q3, Q4, Q10]

3.0 GIANT PLANET MAGNETOSPHERES

All giant planets have strong magnetic fields and robust radiation belts that peak in intensity within a few planetary radii. The giant planets are also host to large satellites, many of which reside inside the magnetic envelope of the giant planet (within a few 10s of planetary radii), forming mini solar system analogs. Several of these moons display strong evidence for surface (Titan) and sub-surface (Europa, Ganymede, Enceladus) liquid, and as such are important targets in the search for habitable environments beyond Earth (see previous chapters). Of the terrestrial objects in our solar system only Earth, Mercury, and Jupiter's moon Ganymede have significant internal magnetic dynamos – providing magnetic shielding to at least some latitudes on the surface. But the magnetospheres of giant planets shield the solar wind from satellites that are embedded inside (while exposing them to weathering by magnetospheric plasma – which might be more extreme). Magnetosphere's within magnetosphere's, such as Ganymede at Jupiter, might provide particularly safe havens for life in otherwise radiation heavy environments. All of this makes the magnetospheric systems of the giant outer planets an excellent place to test whether having a magnetic field is required in order to have environments that can support life.

Despite decades of study at the Earth, numerous questions related to magnetism and magnetic environments remain, and, while modern models and modeling techniques become ever more sophisticated, more data points are needed to train and validate models. This is achieved by investigating magnetic systems in addition to modern day Earth. The relatively new study of the geomagnetic history of the Earth via rock and fossil records is one way scientists catalog the magnetic past of our own planet. The only remaining means to add needed data points - to validate and create needed predictive models - is by studying planets in our solar system with robust magnetic fields: the Outer Planets.

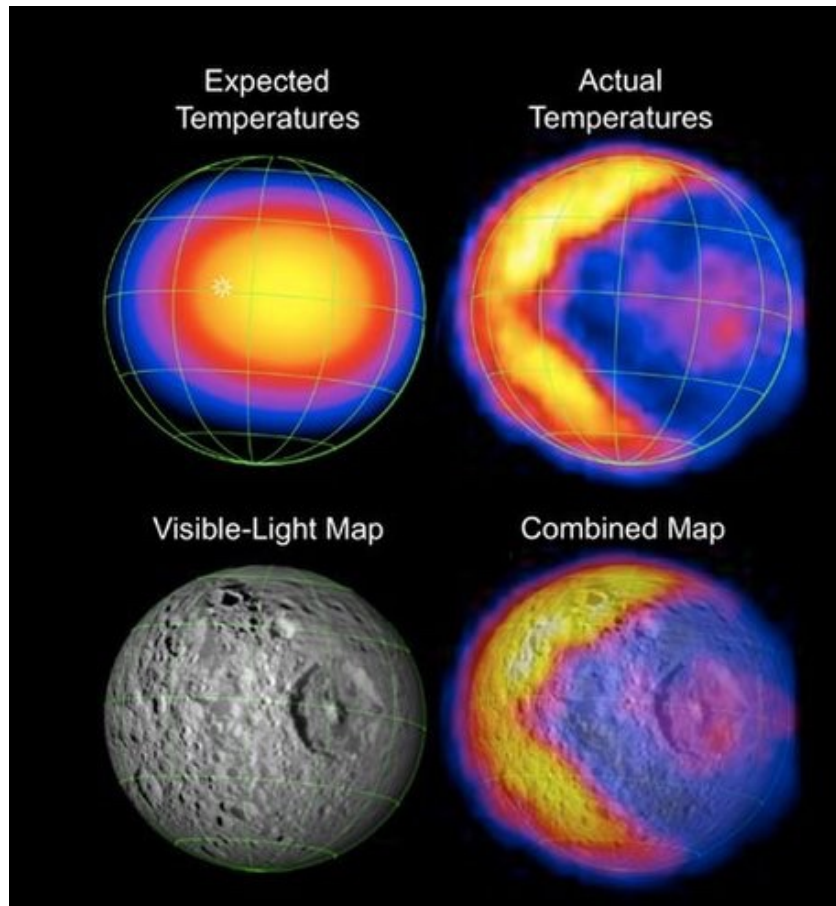
Studying the magnetospheres of the Outer Planets not only deepens our understanding of the Earth's magnetosphere and the habitability of magnetic environments in our solar system, it also helps us to understand the increasing wealth of data on the environments of 'exoplanets', planets around other stars. It is probably not sufficient that a planet have a watery atmosphere to support life, especially those around M-class stars (a rather active star type as compared to our own middle-aged G-type star) – it may well also need a magnetic field, like the Earth. Techniques to remote sense magnetic fields are few and challenging – one way is to look for aurora, light emitted from near the magnetic poles of a planet with a sufficiently strong magnetic field. Another might be to observe characteristic electro-magnetic polarization and yet another to observe kilohertz range radio emission that has been associated with aurora at Jupiter and Saturn. As with all these questions, studying these processes in the only planets with strong magnetic environments beyond Earth, the Outer Planets, is the only way to provide needed data points to our currently fledgling understanding.

In this section we highlight a few extant mysteries directly related to magnetospheres, which can be uniquely addressed by studying our own Outer Planets:

1. How are satellite surfaces effected by magnetospheric interactions?

Planetary plasma processing of the icy surfaces covering potential life-harboring sub-surface oceans weathers and modifies the surface of these moons in ways that are currently poorly understood. For example, Uranus' moons are the darkest in the solar system (displaying literally black surfaces) that may be due to radiation weathering. Longitudinally organized darkening on Saturn's Tethys and Mimas satellites has been linked to energy-dependent magnetospheric plasma bombardment.

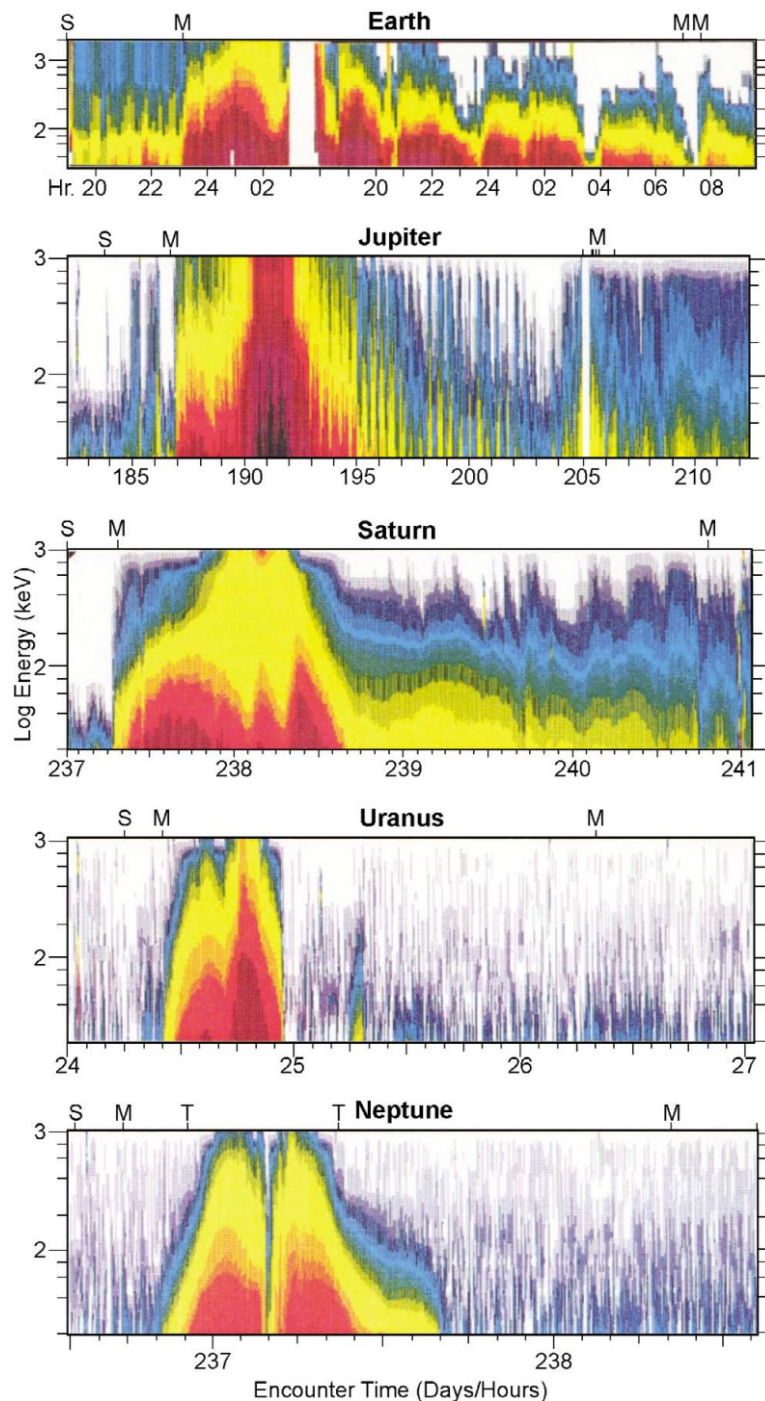
If viewed by the human eye, a subset of outer planet satellites have quite different reflectance spectra than the bright white of objects such as Enceladus and Europa. Saturnian satellites Rhea, Titan, Hyperion, and Iapetus; Uranian satellites Ariel, Titania, and Oberon; Neptune's satellite Triton; and Pluto and Charon would present average colors ranging from essentially neutral (i.e., washed-out yellowish to reddish colors) to pronounced yellow (Triton) to shades of orange (Titan, Pluto, and Iapetus darkside). The near-infrared (NIR) H₂O bands in the spectra of the Uranian satellites and Hyperion require a component dark and spectrally flat and the rings of Uranus are very dark in the visual (VIS) and NIR. Cometary nuclei also appear to be dark and often spectrally



reddish. Accumulation of inorganic and organic cometary and meteoritic dust onto these surfaces would certainly contribute dark materials and charged particle irradiation on H₂O:CH₄ clathrate (without and with NH₃), and on several other simple ice mixtures provide chemical changes in exposed surfaces of these materials in the outer solar system that could explain the observed darkening. Why the Uranian satellites should be especially affected remains a mystery.

[Q3, Q4, Q6, Q7, Q10]

2. How are planetary radiation belts formed and maintained?



All of the strongly magnetized planets of the solar system (Earth, Jupiter, Saturn, Uranus, and Neptune) have robust electron radiation belts at relativistic energies. Acceleration of electrons to relativistic energies within strongly magnetized space environments is clearly a universal process and not one that is peculiar to the special conditions that prevail at Earth or any other specific planet. It is of substantial interest for generalizing space environment acceleration processes to determine the similarities and differences between the radiation belts of these five accessible environments. Are the intensities and characteristics of these environments governed by the same processes and in a predictable and scalable fashion? A notable feature of Uranus is that its electron radiation populations are as intense as any others, whereas its ion populations are anemic. The conditions in outer planet magnetospheres are in some aspects very different to Earth, for example the large tilt of Uranus' spin axis or the strong mass loading with ejected moon material at Jupiter and Saturn. Since our solar system shows several planets with a large number of moons or a strong axial tilt, similar cases are expected for exoplanets.

Is anywhere in Jupiter's magnetosphere safe (for life)? Why are there very high-energy particles far from Jupiter (not just in the radiation belts?)

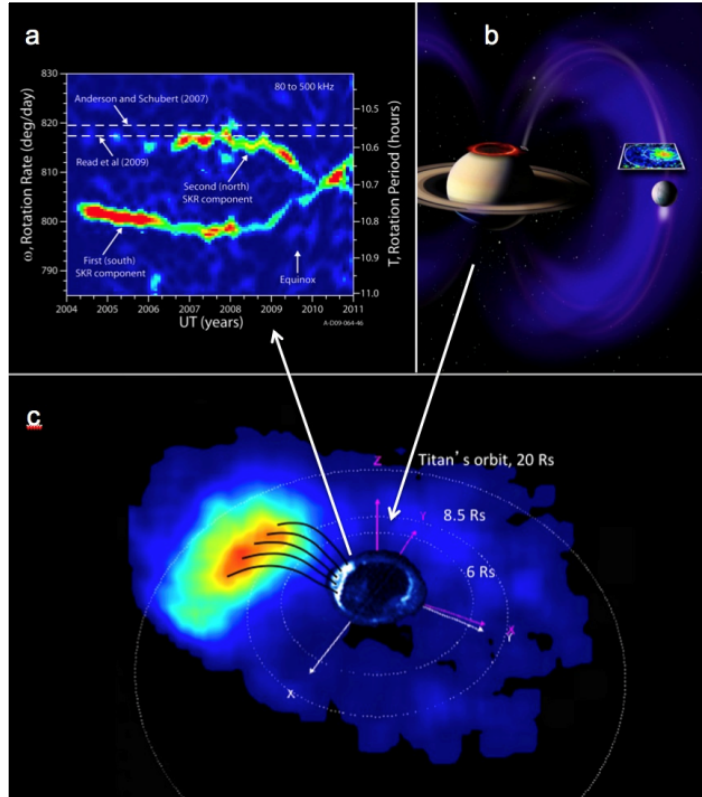
To date it is a mystery why there are relativistic electrons as much as 100 planetary radii away from Jupiter, a region far away from the radiation belts where no stable particle trapping is possible due to frequent reconnection, magnetospheric dynamics and reconfigurations. This presumably is because we do not fully understand the life cycle of a charged particle. Most magnetospheric particles originate from ionization of ejected moon material and, while plausible mechanisms have been suggested for the subsequent heating of initially cold plasma, mechanism(s) that can provide system wide heating to produce and maintain the very high energy electron distributions observed remain elusive.

[Q6, Q7, Q9, Q10]

3. What is the mechanism causing periodic planetary radio emission?

Outer planet magnetospheres are in some aspects simpler than Earth's. For example Jupiter's magnetosphere may, to first order, be unaffected by solar wind. Saturn's proton radiation belts can be described with a small subset of the variety of processes relevant at Earth. We think we know the rotation rate of Jupiter accurate to several decimal places – but this is from auroral radio emissions – the same types of radio emissions that are now known to be slowly varying and to display dual periods at Saturn. Why these ostensibly equivalent phenomena manifest differently at the two planets is arguably one of the greatest remaining mysteries following the Cassini mission at Saturn.

[Q7, Q10]



4. How are the mass and flux budgets of Jupiter and Saturn balanced?

On long timescales we expect magnetospheres to be balanced in terms of how much mass enters and leaves, and how much flux opens and closes. Mass sources at the outer planets include the moons Io (Jupiter) and Enceladus (Saturn), and to a lesser extent the solar wind. However, in situ observations by both fields and particles instruments have indicated that the mass loss from processes such as magnetic reconnection is not enough to balance the mass input. How can this discrepancy be resolved? Can physical mechanisms such as the Kelvin-Helmholtz Instability account for a significant amount of mass transport? Future missions may be required to target specific magnetospheric regions (for example the under-sampled dusk-side magnetosphere) in order to take relevant in situ measurements.

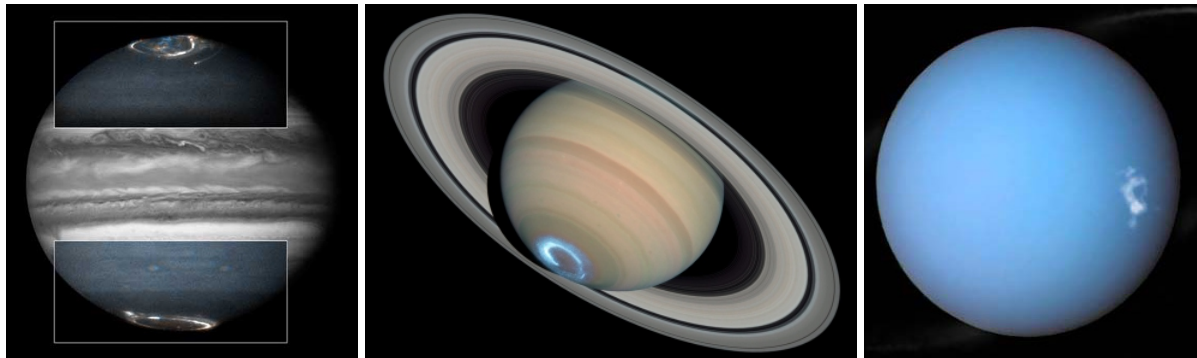
[Q7, Q9, Q10]

5. What is the link between auroral configuration, emission and magnetic field topology?

Auroral emissions are generated above the ionosphere at kilometric (radio) wavelengths (1–1,000 kHz). The emission is thought to be generated by the Cyclotron Maser Instability (CMI) around the magnetic poles and therefore is a remote marker of planetary rotation.

Understanding the circumstances under which planetary radio emissions are generated is of prime importance for using them to detect exoplanetary magnetic fields (important for the development and protection of atmospheres and life). Unlike our Solar System, eccentric and complex orbital characteristics appear to be common in other planetary systems, so that the understanding of radio emission produced by Uranus and Neptune could have profound importance for interpreting future radio detections of exoplanets.

[Q7, Q9, Q10]



Auroral features on Jupiter (left), Saturn (middle), and Uranus (right) are produced by magnetospheric interactions.

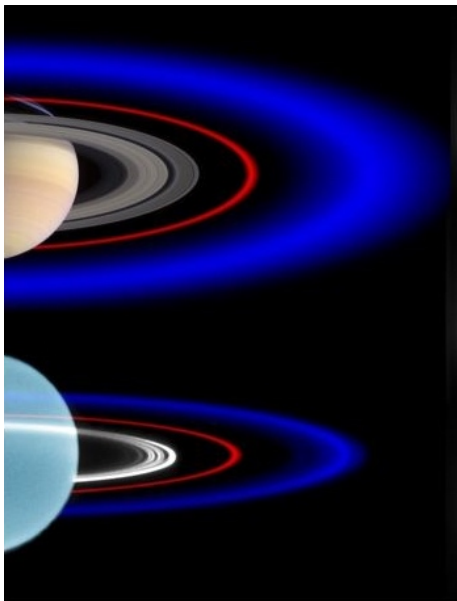
4.0 GIANT PLANET RING SYSTEMS

Investigations of planetary rings can be closely linked to studies of circumstellar disks. Planetary rings are accessible analogs in which general disk processes such as accretion, gap formation, self-gravity wakes, spiral waves, and angular-momentum transfer with embedded masses can be studied in detail. To quote “Vision and Voyages”: *“Exploring the rings of Saturn, Uranus, and Neptune is of high scientific priority, not only to deepen understanding of these giant-planet systems but also to obtain new insights into exoplanet processes and their formation in circumstellar disks, albeit of enormously different scale.”* The highest-priority recommendation on rings in the decadal survey was accomplished: to operate and extend the Cassini orbiter mission at Saturn.

While Cassini data continue to reveal a wealth of new information about Saturn’s rings, even after the end of the Cassini mission, progress has also come from Earth-based observational and theoretical work as recommended by the decadal survey and others. For example, ring systems

were recently discovered around the largest Centaur, Chariklo, and around a dwarf planet, Haumea. Opportunistic imaging of Jupiter’s ring with Juno will also likely reveal more detail about its own structure and evolution. However, the unique ring systems of Jupiter, Uranus, and Neptune are ripe for additional study.

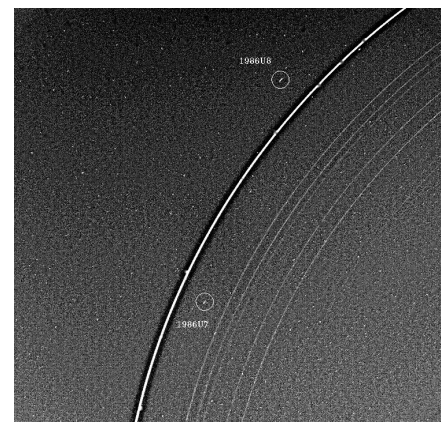
- What can the significant differences among ring systems teach us about the differing origins, histories, or current states of these giant-planet systems?
- Can the highly structured forms of the Uranus and Neptune ring systems be maintained for billions of years, or are they “young”? Are their dark surfaces an extreme example of space weathering?
- What drives the orbital evolution of embedded moonlets; how do they interact with their disks?
- What drives mass accretion in a ring system?



1. What is currently causing ring structures to change or evolve?

Cassini has revealed that significant structural changes in Saturn’s D and F rings have occurred on decadal and shorter timescales. Ground-based monitoring has detected similarly fast changes in the rings of Neptune and possibly Uranus. The mechanisms behind these changes remain mysterious, and it is highly desirable to see these changing structures in greater detail and to monitor them for future change. The Saturn ring system is significantly different from the ring systems of Jupiter, Uranus and Neptune and these differences provide information on the different conditions around these planets in the past. Understanding changes and evolution in ring systems has implications for processes at work over the history of the solar system.

Small moons that orbit within or just beyond a ring or ring system (“ring-moons”) act as tracers of a system’s past and present dynamics, in addition to generating a wide variety of structure within the rings. For example, tracking variations in the orbit of tiny Methone placed constraints on the mass of its larger neighbor Mimas, and the mutual perturbations of the closely-packed inner moons of Uranus tell us that the system looked much different just millions of years ago. Ring-moons also sculpt the rings, create gaps or partial gaps, spiral density and bending waves, and wavy-perturbed ring edges. Discovering and tracking such moons is an important goal with the direct detection of orbital migration also remaining a major goal, either for moons interacting with the rings or for embedded “propeller” moons, as these reflect processes occurring in proto-planetary disks. The past and present conditions of the ring disk are related to the conditions for satellite formation and help us understand how ring and satellite systems evolve.



[Q1, Q2, Q7, Q10]



An incredible amount of detailed structure is visible in Saturn's rings.

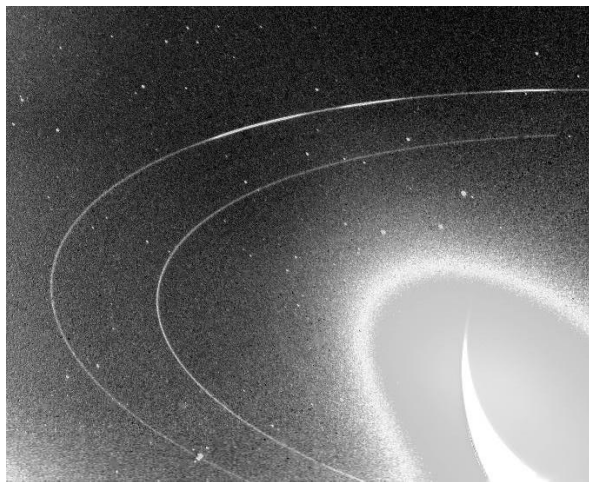
2. What is the composition of ring systems, and how does that composition vary with time and space?

Cassini data show that the composition and thermal properties of particles in Saturn's rings, as well as the characteristics of regolith on larger ring particles, vary over different regions of the rings, for reasons that need to be better understood. The overall composition of Saturn's rings, remarkably rich in water ice, is an important constraint for the origin of the rings and possibly the Saturn system. Large planetary ring systems such as Saturn's provide information on the meteoroid flux and the pollution rates for the system and interconnection with the moons, important for understanding the origin and evolution of Saturn's ring system.

The chemical and physical properties of Uranian and Neptunian ring particles are almost completely unknown. It is highly desirable to characterize them for comparative study. Planetary ring systems interact with both the central planet and with the moons as well as collecting dust from infalling interplanetary material. Determining the composition and physical characteristics of ring particles will inform our understanding of the solar system's past.

[Q1, Q7, Q10]

3. How old are the known ring systems, and how did they originate?



Why does a massive dense disk surround Saturn alone? Why does only Neptune have arcs in its dense rings? Why is Jupiter the only planet without dense rings of any kind? What can these differences teach us about the differing origins, histories, or current states of these planetary systems?

Incomplete ring arcs are seen circling Neptune in this Voyager image

Cassini data have fueled significant progress on the ongoing questions about the age and origin of Saturn's rings, but it is still unclear whether the rings are young (100 Myr) or old (4 Gyr), as no single model explains all the data without difficulty. It is now even more desirable to bring our

knowledge of other planetary ring systems up to a level where meaningful comparative studies to Saturn's rings can be undertaken.

Chariklo, the largest Centaur, was recently discovered to have two rings and rings were found around the dwarf planet, Haumea, as well. These are the first objects besides the giant outer planets detected to have rings. What other bodies might have ring systems and how do they originate and evolve?

[Q1, Q2, Q7, Q10]

4. What can rings tell us about their planetary surroundings?

As delicate dynamical systems covering vast areas, rings sometimes function as useful detectors of their surrounding environment. The structure of the planet's gravity and magnetism, changes in the orbits of its moons, and the population of meteoroids in the outer solar system are all illuminated by phenomena observed in rings.

[Q1, Q2, Q7, Q10]

5. What can rings tell us about exoplanets or about protoplanetary disks?

Planetary rings are an accessible natural laboratory for disk processes. Observed inter-particle interactions and disk-mass interactions, such as ring-moon interactions, and the behavior of propeller-like objects embedded in the ring disk, provide windows onto the origins and operations of exoplanet systems and of our own solar system in its early stages.

Rings could be observed around transiting exoplanets, possibly yielding constraints on the planet's spin and interior structure.

[Q1, Q2, Q7, Q10]

5.0 GIANT PLANETS' MOONS

The diversity of the moons in the outer solar system has much to teach us about physical processes that have played out as the solar system evolved. The most pristine satellites record conditions from the earliest time of solar system history. The divergence of others as different evolutionary paths led the moons to become such unique worlds over the last 4.5 BY is a fascinating challenge that we are only beginning to understand. The prospect that many moons harbor subsurface oceans of liquid water raises the exciting possibility that many habitable niches exist in our solar system.

The satellite sections that follow begin with the most *pristine and primitive* bodies. The least evolved [e.g. Umbriel, albeit based on limited data] have heavily cratered surfaces, near or at saturation, and may have undergone differentiation to a limited extent, if at all. Some show volatile mobility [e.g. Callisto, Iapetus] with sputtered atmospheres and/or regional frost deposits. Some feature surface evolution due to tectonics [e.g. Tethys, Ariel, Miranda].

Following the primitive satellites, the more evolved satellites are discussed in individual subsections; these are the most compelling worlds for future exploration, from the Jupiter system to the Neptune system:

Ganymede has an evolved, differentiated interior and is the only satellite known to generate its own magnetic field, but exhibits a moderately old surface that has undergone extensive tectonic activity. It also has strong evidence of a subsurface ocean at depth.

Europa has a very youthful surface (possibly active) that has undergone significant tectonic activity. Its likely subsurface ocean may possess all the ingredients for life and is a current focus of our quest to understand habitable zones in subsurface oceans.

Io and *Enceladus* feature ongoing active eruptions (silicate and icy, respectively), re-surfacing, and tectonic activity due to tides. *Io* is the most tidally heated world in our solar system, and is key to understanding this fundamental process. *Enceladus*' subsurface ocean is thought to be habitable based on Cassini results.

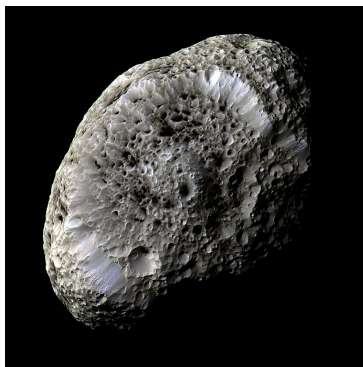
Titan has a youthful surface with geology recognizably similar to Earth (river channels, lakes and seas, mountains, dunes, and few impact craters) and a methane cycle analogous to Earth's water-driven meteorology and hydrology, with clouds, rainfall, lakes and seas. *Titan* also hosts a subsurface ocean.

Triton has a highly evolved interior (and perhaps an ocean), a youthful surface, and an atmosphere in vapor pressure equilibrium with surface frost.

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

1. What are the compositions (surface and bulk) and interior structures of the satellites, and what do they tell us about satellite formation and evolution processes, and formation locations?

Compositions, especially of volatile materials, preserve information about formation conditions, subsequent modification (both endogenic and exogenic), and volatile loss and exchange across the different giant-planet systems. Comparisons of diversity of mid-sized satellites within the Saturnian and Uranian systems, and comparisons between the two systems, illustrate dramatically different possible evolutionary paths and driving factors behind them. Another important question is whether the Uranian satellites are the result of system formation processes similar to those at other giant planets or are related to other events. Understanding of the bulk composition of the satellites will better constrain their interior structures and evolution. Laboratory work will help



Hyperion

with interpretation of observations. Understanding surface compositions and the processes that drive them are also a high priority, e.g., how solar energy affects surface processes and how volatile re-distribution is expressed. Contrasting bright-dark surfaces (at the global and local scale) on *Iapetus* are the direct result of insolation-driven volatile redistribution, which may also explain the evolution of *Hyperion*'s unusual surface and may have operated at *Callisto* to erode the surface and form small-scale surface topography.

[Q1, Q2, Q4, Q6, Q10]

2. What processes drove satellite formation and evolution and allow interior oceans and long-lived endogenic activity on even small satellites?

2.1 The dynamics of satellite formation processes have produced diverse systems: four large satellites at Jupiter, one large and seven mid-sized (>200 km diameter) satellites at Saturn, no large and five mid-sized satellites at Uranus, and two mid-sized (originally regular) satellites at Neptune along with the larger, irregular satellite Triton, believed to have been gravitationally captured. Understanding the nature of these systems of satellites, as well as of the individual satellites themselves, provides key constraints on the processes involved in their formation.

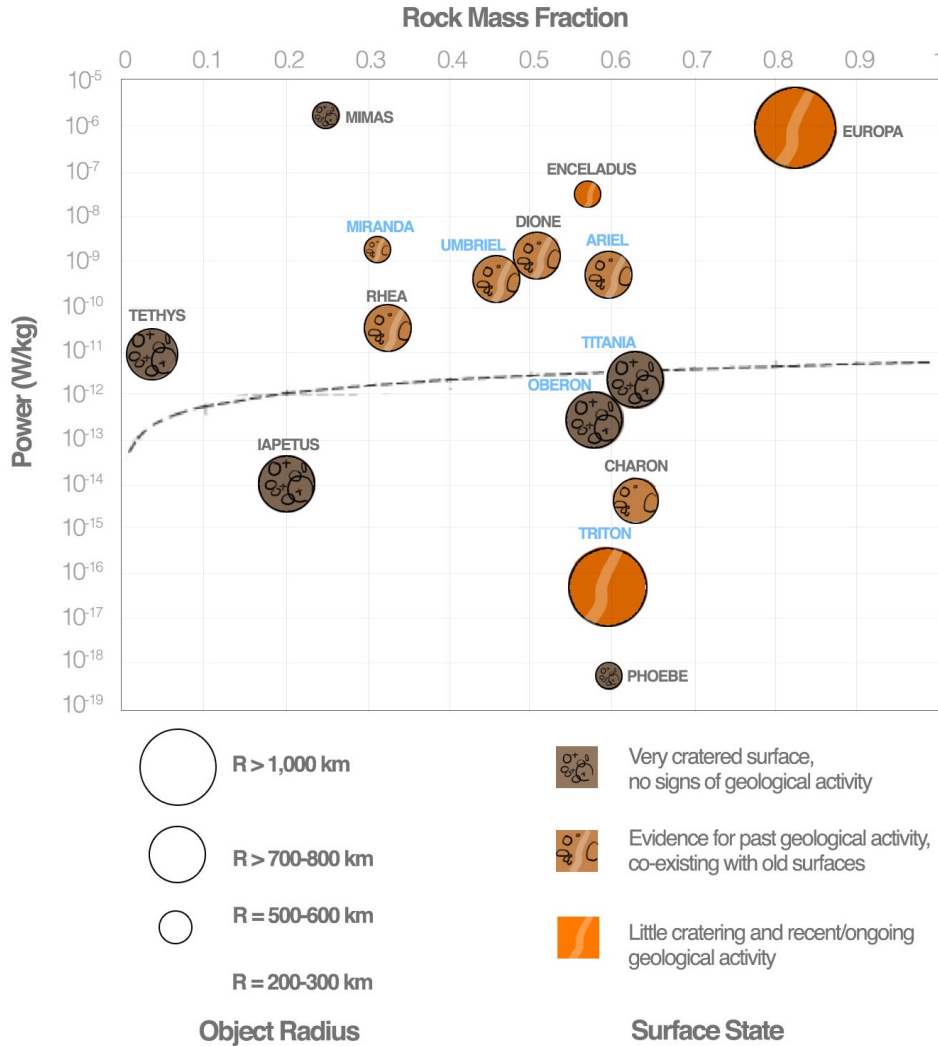
[Q1, Q2, Q3, Q4, Q7, Q10]



Satellite systems of Jupiter, Saturn, Uranus, Neptune (top to bottom) to scale.
http://solarsystem.nasa.gov/multimedia/display.cfm?Category=Planets&IM_ID=181

2.2 The energy sources available to the satellites are critical to their histories. Counterintuitively, some of the most active satellites (currently or in the recent geological past) are the smaller satellites, *e.g.*, plumes venting from the south polar terrain of 504-km-diameter Enceladus and coronae (perhaps endogenic) exceeding 300-km in size on 472-km-diameter Miranda. While, in comparison, Iapetus (1470-km diameter) cooled so quickly that it preserves the shape of a body in hydrostatic equilibrium with an early 16-hour rotation period (current rotation period is 79.3 days). After Europa, Enceladus, and Mimas, the satellites with the highest available power are Dione, Miranda, Ariel, Umbriel, and Rhea (see figure). Explaining the energy budgets of the tidally heated satellites and their evolution through time remains challenging. The coupled evolution of satellite systems, and tidal interactions in particular, are important long-term sources of energy that need to be better understood through exploration as well as modeling.

[Q4, Q6, Q7, Q10]



Energy budget potentially available to icy satellites expressed as a function of their rock mass fraction (i.e. content in radioisotopes) and tidal heating (power produced per kg, multiplied by k^2/Q). The global geological state of the various satellites is sketched as a marker of endogenic activity and the possible presence of a deep liquid layer at some point in the evolution of these objects. The dashed line indicates current-day heating due to natural decay of radioisotopes in the rock. (After Castillo-Rogez and Lunine 2012, with updated information on Charon from New Horizons data (Castillo-Rogez personal communication).)

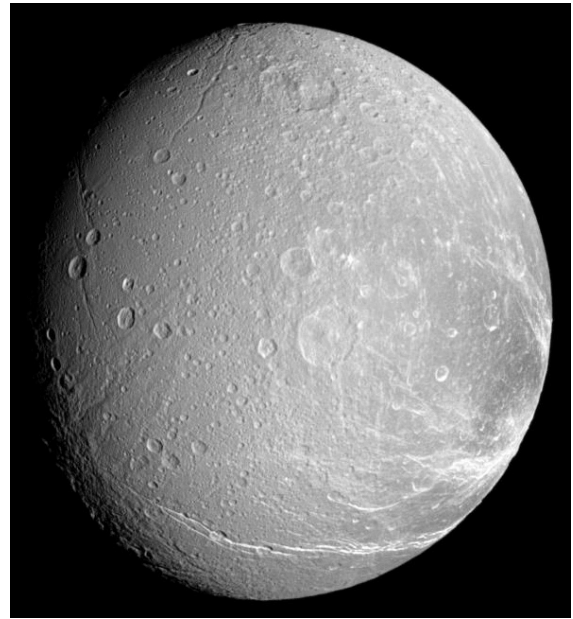
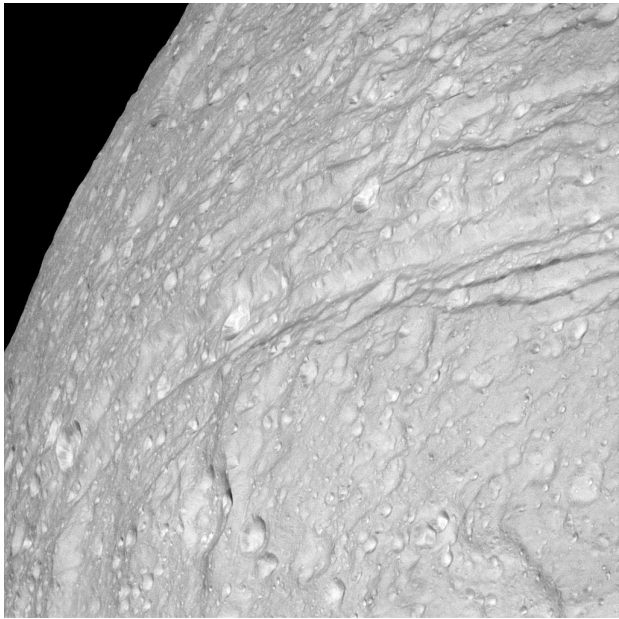
2.3 Among the mid-sized satellites, Enceladus exhibits strong evidence for a sub-surface ocean while Dione, Rhea, Titania, and Oberon also have potential to host interior oceans. Determining the presence and natures of sub-surface oceans, especially whether liquid water is in direct contact with rock interiors as is suspected at Enceladus and Europa, is crucial to understanding the evolution and potential habitability of these bodies and how materials are processed within them. Investigating worlds both with *and without* oceans will be key to understanding what conditions are necessary for oceans to form.

[Q4, Q6, Q7, Q10]

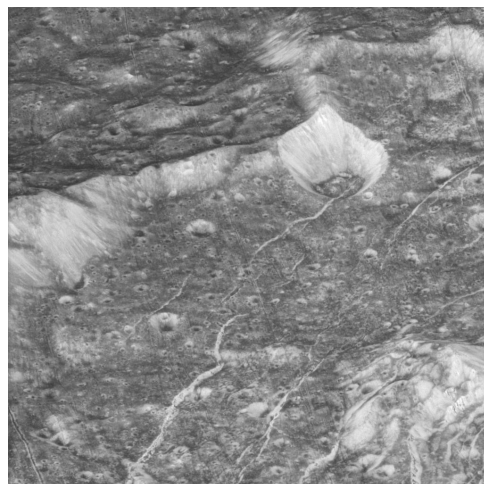
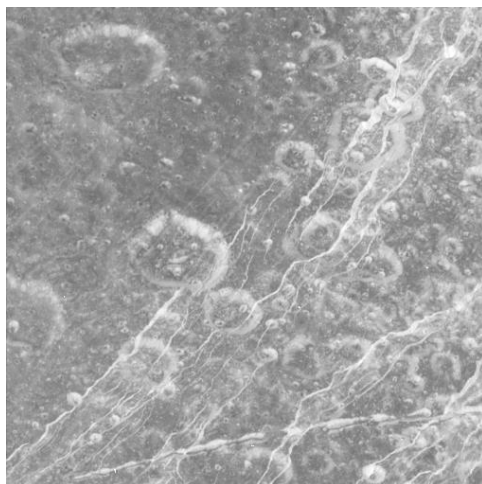
3 What processes have shaped, and are continuing to shape, the satellites, and what controls which of the wide variety of observed processes occur?

3.1 The surfaces of the mid-sized satellites exhibit diverse expressions of geologic processes, each reflecting its unique history. In many cases, similar conditions and processes have led to extremely different expressions in landforms, *cf.* extension localized in the form of the Ithaca Chasma system on Tethys and globally distributed in faulting at a variety of scales on Dione.

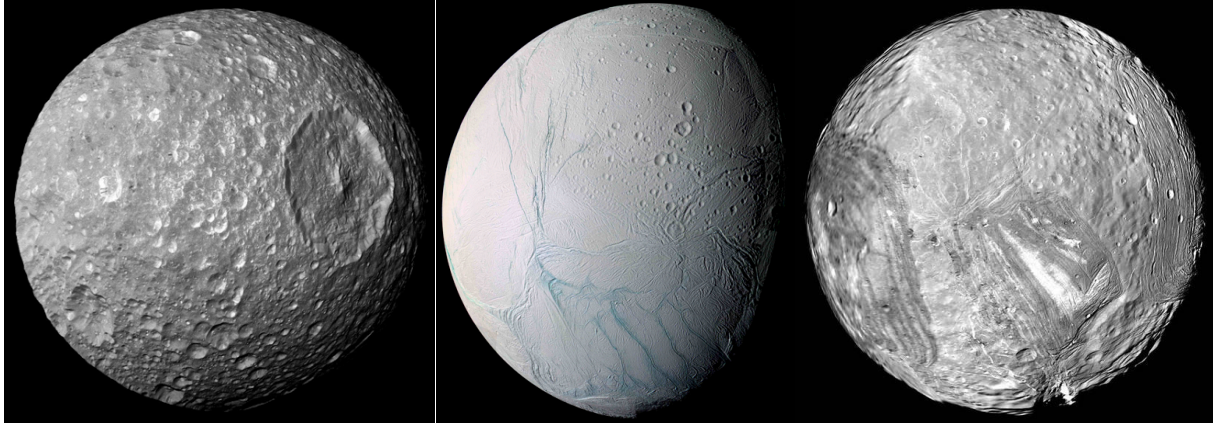
[Q6, Q7, Q10]



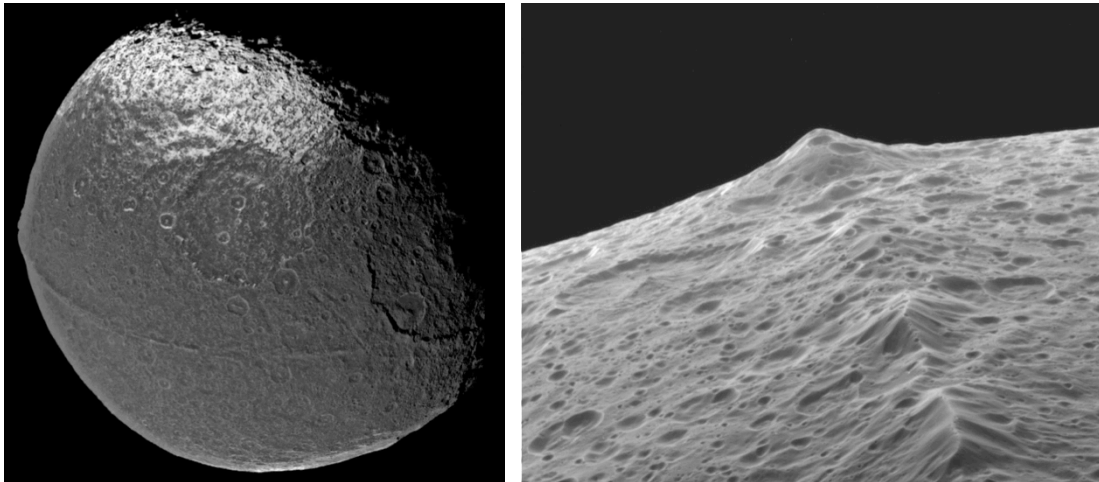
Ithaca Chasma, Tethys (left) and fractures on Dione (right)



Fractures on Dione at pixel scales: 230 m (left) and 23 m (right)



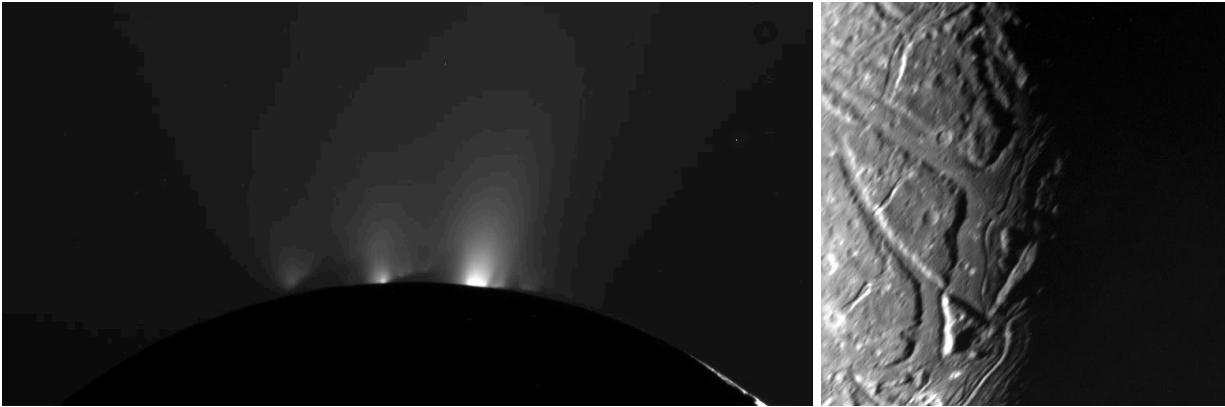
Comparably sized, vastly different: Mimas (left; 396-km diameter), Enceladus, (middle; 504-km diameter), Miranda (right; 472-km diameter). (Not to scale.)



Giant impact basins and equatorial ridge on Iapetus

3.2 Cryovolcanism has been particularly difficult to identify on most icy satellites, perhaps an indication that it occurs only rarely or in integral association with tectonism, but the challenge may also be because it is difficult to identify or interpret in the context of icy materials. The only definitive example of active cryovolcanism is Enceladus' plume. There is also evidence that suggests cryovolcanism on Triton, Europa, Titan, and Pluto (discussed in other sections). Intriguingly, Ariel has features that are strongly suggestive of extrusive cryovolcanism in the form of viscous flows.

[Q4, Q6, Q7, Q10]



Enceladus' south-polar plumes (left) and potential cryovolcanic flows on Ariel (right)

3.3 Impact crater distributions and cratering statistics have implications for understanding solar-system evolution, projectile populations and temporal changes therein, and bombardment history throughout the solar system. Crater morphologies and their distributions provide valuable probes of target subsurface structures and properties, *e.g.*, lithospheric thickness, heat flow, and material properties through time, as well as spatial variations therein across the surfaces of individual satellites (*e.g.*, the large relaxed craters at Enceladus' north pole compared to the essentially crater-free South Polar Terrain).

[Q3, Q4, Q6, Q7, Q8, Q10]

3.4 Irregular satellites

As captured bodies, irregular satellites provide information about the population(s) from which they originated and the distribution of material within outer planet systems. See discussion in the Small Bodies Assessment Group (SBAG) Goals Document:

https://www.lpi.usra.edu/sbag/goals/SBAG_GoalsDoc_ver.1.2.2016.pdf

[Q1, Q4, Q10]

5.2 Ganymede Science Objectives

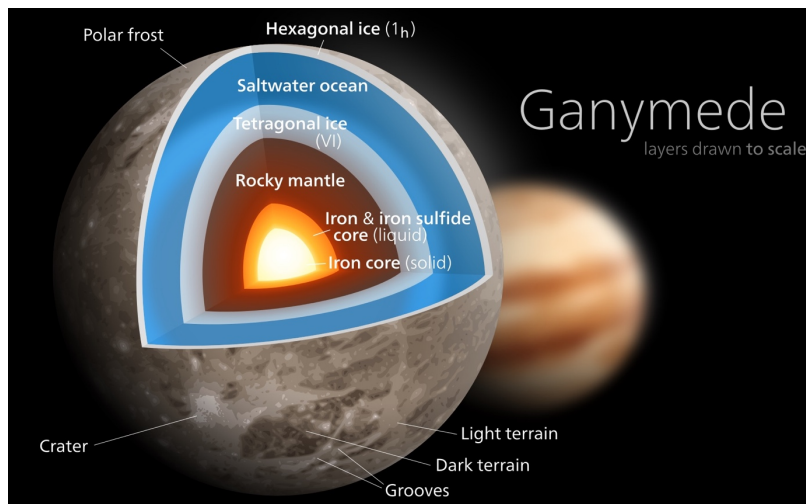
The Galilean satellite Ganymede shows a tremendous diversity of surface features. The factors influencing its origin and evolution are related to composition (volatile compounds), temperature, density, differentiation, volcanism, tectonics, and the rheological reactions of ice and salts to stress, tides, and space interactions that are still recorded in the present surface geology. The record of geological processes spans from possible cryo-volcanism, through tectonism, to impact cratering and landform degradation. Remarkably, Ganymede has its own magnetic field, influencing the surface exposure to Jupiter's plasma environment, and indications of a subsurface ocean at depth.

1. Interior Structure. What is the nature and history of Ganymede's interior structure? What is the nature of Ganymede's subsurface liquid ocean? What is the origin and evolution of Ganymede's dynamo magnetic field?

Gravity and magnetic field evidence point to a fully differentiated structure for Ganymede, in that its inferred moment-of-inertia is the lowest of any solid body in the solar system and it possesses its own intrinsic dipole magnetic field. Ganymede is thus inferred to be differentiated into a massive icy shell, rocky mantle, and iron core. The iron core must be at least partially molten to sustain a dynamo. Magnetic field evidence has been further interpreted to imply that Ganymede also possesses an induced field in the manner of Europa and Callisto, and thus possesses a conducting layer closer to its surface, presumed to be a layer of salty water sandwiched between a less dense ice I layer above and denser, higher pressure ices below.

Two critically important questions remain. The first is the very existence of the dipole field. The field requires convection of liquid iron (or liquid iron-sulfur, etc.), which implies a minimum power output from the core. All models to date, even those that invoke tidal heating episodes in the past, have failed to yield the power necessary at the present day. The second question is how the evolution of Ganymede's interior directly or indirectly was responsible for the resurfacing of much of Ganymede, creating its bright terrains. Did Ganymede differentiate relatively late in its history? Was an internal melting and refreezing episode driven by passage through a tidal resonance? Or did something completely different occur? Furthermore, why did Callisto not follow this path?

Answers to these questions will rely on improved measurements of Ganymede's gravity and magnetic field, including non-hydrostatic components of the former and time variability of the latter. Global topographic measurements as well as determination of the tidal response of the surface (Love numbers) will facilitate interpretation of the gravity field, determine the thickness



of the upper ice shell, and constrain the depth of the (putative) internal ocean and possible layers of exotic salts. Further constraints on the characteristics of the subsurface ocean may be gleaned from more detailed observations of the variable aurora. Seismic information would be definitive. The nature of Callisto's and Titan's interior are directly relevant to this objective.

[Q1, Q2, Q3, Q10]

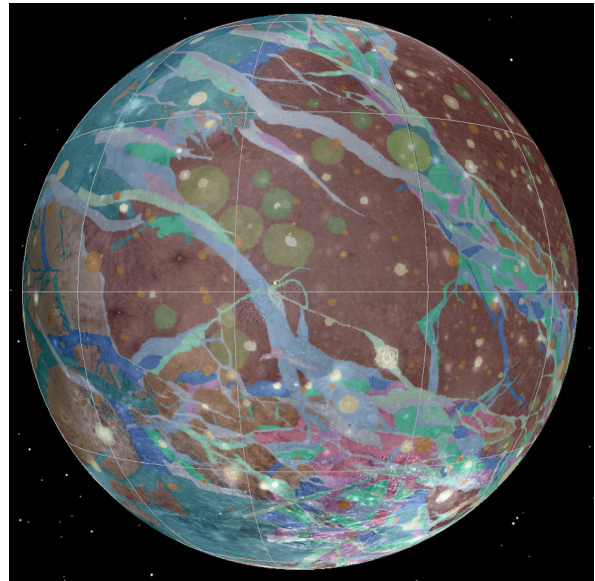
2. Surface geology. What are the geologic processes responsible for Ganymede's surface features? What are the ages of Ganymede's terrains and landforms? Has cryovolcanism and or diapirism played a major role in renewing the surface? Has lithospheric spreading occurred? What are the stress mechanisms that have shaped the surface tectonics? What is the role of volatile migration and landform degradation on its surface?

Ganymede's mix of young and old terrain, ancient impact basins and fresh craters provides landscapes dominated by tectonics, icy volcanism, and the slow degradation by space weathering. Understanding this icy satellite's surface processes can help us understand how icy worlds evolve

differently from rocky terrestrial planets. Ganymede's surface is subdivided into dark, densely cratered ancient plains (perhaps essentially primordial and somewhat similar to the surface of Callisto), covering about 1/3 of its total surface and bright, less densely cratered, heavily tectonized, grooved terrain. In addition to craters, dark terrain also displays hemisphere- scale sets of concentric troughs termed furrows, which are probably the remnants of vast multi- ring impact basins, now broken up by subsequent bright terrain tectonism. This type of terrain appears relatively dark due to the addition of a non-water ice contaminant that appears to be concentrated at the surface by a variety of processes including sublimation, sputtering and mass wasting.

Bright terrain separates the dark units in broad fault-bounded lanes up to several hundred kilometers wide, termed sulci, typically comprised of linear or curved parallel fault scarps forming closely spaced grooves. The bright terrain units formed predominantly at the expense of dark terrain through a poorly understood process of volcanic and tectonic resurfacing, causing the partial or total transformation of dark terrain into bright terrain by tectonism. (Generally, grooved terrain represents rifts created by extensional stress). Several caldera-like, scalloped depressions, termed paterae, found in the bright terrain represent probable volcanic vents, and ridged deposits in one of the largest paterae have been interpreted as cryovolcanic flows.

The geologic process of resurfacing bright terrain is incompletely understood. Smooth units which embay other surface units such as crater rims, in some parts less densely cratered, are thought either to represent cryovolcanic flows, extruded as icy slushes or to be issued from mass wasting processes along slopes. The smoothest units also exhibit some degree of tectonism, implying that cryovolcanism and tectonic deformation are closely linked. Despite much effort to understand the patterns of Ganymede's grooves (at global, regional, and local scales), we do not yet understand the stress mechanics that have shaped the surface, and the possible roles of (for example) non-synchronous rotation, true polar wander, and convection. Although the ultimate driving mechanism for groove formation is uncertain, there are many intriguing possibilities that it may be tied to the internal evolution of Ganymede and the history of orbital evolution of the Galilean satellite system.



Impact features on Ganymede exhibit a wider range of diversity than those on any other planetary surface. They include vast multi-ring structures, low-relief ancient impact scars called palimpsests, craters with central pits and domes, pedestal craters, dark floor craters, and craters with dark or bright rays. The subdued topography of Ganymede's oldest impact craters imply a steep thermal gradient in Ganymede's early history, with more recent impact structures reflecting a thicker and stiffer elastic lithosphere. Such an interpretation indicates a much warmer shallow subsurface early in Ganymede's early history than at present.

[Q10]

3. What is the composition and origin of Ganymede's surface materials and how do they change over time?

The chemical composition of the visually dark, non-water-ice material on Ganymede is presently unknown. Organics and hydrated salt are possibilities, but there may also be a component of hydrated sulfuric acid, as has been proposed for dark material on Europa. Given these uncertainties regarding its composition, the component of exogenic material in the Ganymede non-ice material is also unknown, as is whether the material is of a single uniform composition over Ganymede's surface. Understanding how these non-ice materials correlate with the surface geology at a wide range of spatial scales, and whether they are linked to the subsurface at all, will aid in identifying their nature and origin(s).

Large-scale, sublimation-driven landform modification is notably rarer in Ganymede's dark terrain than on Callisto, which may indicate a relative paucity of highly-volatile CO₂ ice in Ganymede's near-surface, which is thought to be the principal force behind sublimation weathering. In addition, Ganymede does not exhibit the same bright ice pinnacles at topographic peaks and crater rim crests as are commonly seen on Callisto, and which are thought to be redeposited water ice. Close scrutiny of Ganymede's dark terrain is therefore key to understanding the role of volatile migration in shaping Ganymede's surface as well as the relative inventories of certain volatiles within the crusts of Ganymede and Callisto.

The composition and physical state of materials on Ganymede's surface will be altered by radiation weathering effects, but what compounds are produced through radiolytic processes on the surface of Ganymede, and their lifetimes and rates of formation, are not known. Determining the abundance and distribution of such compounds on the surface will help inform as to the intensity and type of magnetospheric bombardment over the surface of Ganymede. Defining the temporal cycle of the oxygen species on Ganymede is a specific objective.

[Q10]

4. What are the characteristics of the intrinsic magnetic field of Ganymede (strength, size, variability) and of Ganymede's exosphere and ionosphere?

The properties of Ganymede's magnetic field are not well constrained. These include the size of the magnetosphere, as manifested on the surface by the location of the boundary between open and closed field lines. This boundary may correlate to certain surface and exosphere features if interactions with such features are significant. A key objective of a magnetospheric investigation would be to determine the particle distributions of various species around Ganymede, including what neutral species are present in the exosphere beyond those that have been inferred already. Such an investigation will help characterize Ganymede's exosphere, in particular by defining the morphology and dynamics of its asymmetry, and the extent to which Ganymede's magnetic field generates such asymmetry. It would also aid in identifying the processes of production and loss of the exospheric particles and how such processes vary in space and time. Determining the distributions of charged particles will help in defining the extent, structure and dynamics of Ganymede's ionosphere as well as the nature and controlling factors for the aurorae that have been observed at Ganymede's poles. A final question is whether Ganymede's magnetosphere is strong

enough to prevent Ionian sulfur (which is thought to be present on Europa's surface) from impacting Ganymede's surface.

[Q10]

5.3 Europa Science Objectives

Europa is considered a known Ocean World. Its young surface, energetic environment, and potentially rich inventory of ingredients for life that has likely existed over the lifetime of the solar system makes Europa one of the more promising candidates in the search for life beyond Earth. The Europa Clipper mission will extend our understanding of Europa as an Ocean World. Specifically, it will characterize Europa's ocean and outer ice shell, giving us a better understanding of the ocean environment and its connection to the surface. In addition, the Europa Clipper mission will assess Europa's habitability and provide the needed information to support follow-on missions that advance the search for signs of life.

The following five fundamental topics will likely define Europa science and exploration for the coming decades.

1. How does Europa's Ice Shell Work?

Europa's surface is riddled with fascinating geology, and impact craters are scarce. The surface, with an estimated average age of 40-90 Ma, must be recycled or reprocessed in order to explain its lack of craters. How does this happen? At present, while the preponderance of evidence suggests an ice shell thickness of at least 20 km, arguments for a thinner shell still have observational merit. These open issues inspire a range of questions that address just how Europa's still-active ice shell operates.

The most prevalent of Europa's surface features are its ubiquitous ridges. These are of several types, and the origin of these features is highly debated. Ridges are characterized as single, double, and ridge complexes, and these include both linear ridges, and cycloids, with arcuate cusps that suggest variations in stress over time. These fractures may penetrate just the brittle shell, or completely through the ice shell. These are also thought of as possible conduits for material from the deeper ice shell or ocean to reach Europa's surface. It is generally thought that these ridges are generated via tectonic stresses within the ice shell, and manifest via either strike-slip or tensional displacement. Cycloids may have originated in response to diurnal variations in tidal stress or due to tidal stress plus additional non-synchronous and/or obliquity stresses, or conversely due to the build up of stress and periodic release through formation of tail cracks. However, it has also been shown that the tidal stresses alone are not high enough to break Europa's ice shell. Suggestions for the genesis of fractures from the ocean or ice shell include cracks forming at the ice-ocean interface in response to either stresses from ice shell thickening, ocean overpressure, and/or dike formation propagating cracks through the shell. However, these processes may be difficult to reconcile with the presumed thick ice shell where a brittle elastic layer overlies a ductile layer that may be viscously deforming and preventing fracture. It may be that the combination of tidal and convective stresses may play a role in the formation of these features. However, with very few close flybys of Europa by Galileo, as yet no convincing evidence in any particular direction can eliminate the field of possibilities.



Ridges on Europa

Europa's bands—wide, relatively flat and linear bands of generally darker or newer ice—are regions of presumed production of new surface material, while some might be the sites of destruction of old material. Thought to be perhaps analogous to seafloor spreading centers on the Earth, these features remain incompletely understood. From where does the new material originate? How deep do the bands penetrate into the shell? These questions require better data or new models to reconcile. Some of Europa's bands may be responsible for reprocessing subsumed or subducted material, participating in the cycling of ice and water through the ice shell. This plate tectonic-like process, if confirmed, would represent a major step forward in understanding ice shell processes on Europa.

Europa's enigmatic chaos terrains, including large chaos and microchaos such as pits, spots, and domes, are (thus far) unique in the solar system and as such represent a key to unraveling its geologic activity. The detailed formation mechanism for these features is debated, but all models involve formation in the presence of shallow liquid water, and thus these features are amongst Europa's most compelling for exploration of subsurface liquid reservoirs. Models exist for complete melt-through of the ice shell, however these are kinetically and thermodynamically unfavorable. Other models suggest these features form as a surface expression of various degrees of melting in the subsurface caused by diapirism, convective plumes, and/or tidal heating. These regions are relatively young, and in addition to being likely the best places to search for shallow water within Europa's ice shell, may represent regions of surface-subsurface exchange and the production of new surface material.

Europa's sparse cratering record and the superposition of its many and possibly recently formed surface terrain, represent the major pieces in unraveling Europa's activity and geologic history. Ice shell processes are important to characterize in order to understand whether tidal heating, convection within the ice shell, or thermo-compositional processes are responsible for heat exchange between the ocean and ice, potentially creating a conveyor belt of material through the shell. Because the ice shell is the mediator of mixing between endogenic and exogenic processes, understanding its dynamics would result in a more complete picture of how this icy satellite has evolved through time and have implications for Europa's habitability. Moreover, a better

understanding of these processes can identify likely surface or near surface environments suitable for habitability, which would become the focus of life detection missions.

[Q2, Q6, Q7, Q10]



Chaos terrain on Europa

2. What is the interior structure of Europa?

Galileo gravity and magnetic field data reveal a compelling picture of Europa's likely structure: an ice and water layer of up to ~150 km deep atop a mostly rocky interior. The induced magnetic field detected at Europa is most consistent with an ocean of similar conductivity to that of the Earth within 50 km of the surface.

However, with only 9 close flybys of Europa, both the magnetic field and gravity data are of low fidelity. For instance, the depth and thickness of the ocean layer can only be loosely constrained given assumptions about its conductivity. Gravity data are sufficient to constrain the depth of the ice-water layer to within ~50km, but are insufficient to search for topography on the sea floor, or to confirm the presence of an iron core. Moreover, if Europa has a liquid iron core, these data are insufficient to confirm an intrinsic field, only placing bounds on its maximum strength. This information is a critical part of understanding the energy budget within Europa, which would help constrain whether activity deep in its interior might be sustained until present day, perhaps powering sea floor vents or other activity that could sustain a habitable ocean.

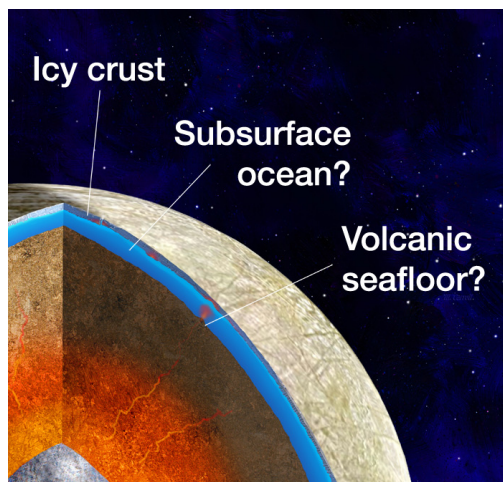
[Q2, Q6, Q7, Q10]

3. What is the distribution of water within Europa?

In the search for life beyond Earth, the mantra has long been “follow the water.” On Europa, the detection of an induced magnetic field all but guarantees the existence of a liquid water ocean. However, if and how this water makes it to the surface is debated. Basal fractures, dikes, and sills could be responsible for direct communication of the ocean with the surface forming ridges or cracks, however whether these could extend through Europa's ice shell is unclear. Many of Europa's surface features could be formed in the presence of water, including chaos, pits, domes,

and spots. While some have argued for complete disruption of the ice shell in these areas, most hypotheses involve melting within the shell via convective, tidal and/or thermo-compositional processes, rather than direct communication with the ocean. In this case ice rising from the ocean interface could be mixed with shallow ice via melting, so the distribution of water within the shallow ice is also provocative. Such features may be attractive targets for landers, and thus understanding which are water rich will be critical to future exploration.

Geological data are inconclusive as to the thickness of the ice shell. Interpretations can be grouped into two classes: thick and thin, the former with estimates ranging from ~15 to 30 km and the latter ~3-10 km. This is an important constraint because this thickness determines, in part, where the vast majority of the immense tidal energy from Jupiter is distributed. If the ice shell is sufficiently thick, the dissipation may occur predominantly in the ice. However, interactions with ocean tides could either amplify or counteract this dissipation, thus better constraints on the ice shell, ocean, and deep interior provide a window into any endogenic activity within Europa's silicate mantle.



Water vapor plumes have been suggested to erupt from Europa's surface by several lines of evidence, including Europa's variable oxygen atmosphere, interaction with the Jovian magnetosphere, its dust environment, and from telescopes. Hubble Space Telescope results suggest that variable plume activity may occur. The location of the detected plumes indicates that either ridges or perhaps chaos regions at high southern latitudes could be the source of water ejected into the European exosphere. This possibility is nonetheless intriguing and the ability to confirm these plumes and look for connections with surface geology would help constrain the provenance of this water.

[Q2, Q6, Q7, Q10]

4. What are Europa's surface, ocean, and interior compositions?

In addition to geologic heterogeneity, Europa's surface shows compositional diversity. Both Voyager and Galileo data showed that the surface is a mixture of dark material within the background ice, but the detailed composition remains uncertain.

Dark material is present along young ridges and their flanks and in the floors of chaos terrains, pits, and spots. These regions are possibly demonstrative of either oceanic material or reprocessed non-ice material within the shell being extruded on or concentrated in the surface. There is also a hemispheric albedo variation, with reddish material blanketing preferentially the trailing hemisphere. It is likely that the hemispheric variations are caused by interactions between surface materials and impacting high-energy particles. Galileo spectrometers suggest these darker materials are rich in magnesium, sulfur, and possibly sodium, but the results are non-unique and the conclusions vary among researchers. Earth-based telescopes suggest similar results. However, whether this represents processing of ocean material, or a mixture of exogenic and endogenic

materials, is uncertain. This material may provide clues to the habitability of Europa's ice shell and ocean.

Based on limited magnetospheric data, Europa's ocean composition is not well bounded, but includes a possible similarity in salinity to that of the Earth. This possibility may come as little surprise, given that the ocean water would have reacted with Europa's silicate interior as the planet differentiated, much as water on Earth would have. However, with the constraint dependent upon the thickness of the ice and ocean, and the non-unique results regarding surface salt composition, much remains to be learned of Europa's ocean composition. Both magnesium- or sodium-bearing salts are consistent with the surface spectroscopy, and this dramatically changes the interpretation of the ocean composition and its interactions with the sea floor. Depending on the rate of surface reprocessing and interactions between the ocean and the seafloor, Europa's ocean could become highly acidic or basic, depending on the assumptions of the model. Thus it is critical to understand this chemistry in order to assess the moon's dynamics and putative habitability, using both fields and direct measurements as well as modeling.

Unraveling the surface and ocean composition can also constrain the composition of Europa's silicate interior. Is there any fundamental difference between the material that formed Europa and the presumably chondritic reservoir from which the terrestrial planets formed? Has the silicate mantle fully reacted with the ocean, or might such processes as serpentinization and dehydration still be underway? The structure of Europa's mantle and core could be better constrained with more gravity science flybys, given that most of what we know is derived from a handful of Galileo passes. Determining, for instance, whether the interior is mostly hydrated, or if it is dry, would provide insight into the activity of Europa's interior over time.

[Q2, Q6, Q7, Q10]

5. Is Europa habitable today? Was it ever? Has life arisen on Europa?

There are a host of interesting planetary targets for exploration. Arguably what sets Europa apart is the issue of habitability. For Europa, this can be broken down into several key components: Does Europa possess the necessary ingredients for life? If not today, did it ever? And if so, has life ever arisen on Europa? For Europa to be habitable, as we currently understand it, water and biologically relevant compounds (iron, phosphorus, nitrogen, etc) must be combined with a stable source of energy and enough time to allow for life to become established. The exact requirements are unknown, but these important considerations represent a maturing picture of what it means to be habitable. This is of course, related to but separate from whether life originates at all.

The four questions above motivate the investigation of Europa's past and present habitability. Given its size, Europa at present likely requires a constant input of energy to maintain geologic activity that may power a biosphere. Constraints on this energy budget are likely more important for modern habitability, since its own internal heat may have been sufficient to permit habitability early on. Such activity could manifest as both surface geology and putative sea floor activity. It is likely that in order to be habitable, Europa's surface, affected by the Jovian magnetosphere and bathed in particles from the Io torus, must be recycled on a rapid enough timescale to deliver biologically relevant oxidants and other limiting nutrients like phosphorus into the ocean. The

distribution of water within Europa is important as well: too much, or too isolated, and the necessary components for life may never be collocated or too diffuse to create niches for life. The chemistry of the moon would regulate metabolic activity of any organisms, and in models the possibilities for the ocean composition range from either too dilute to even toxic.

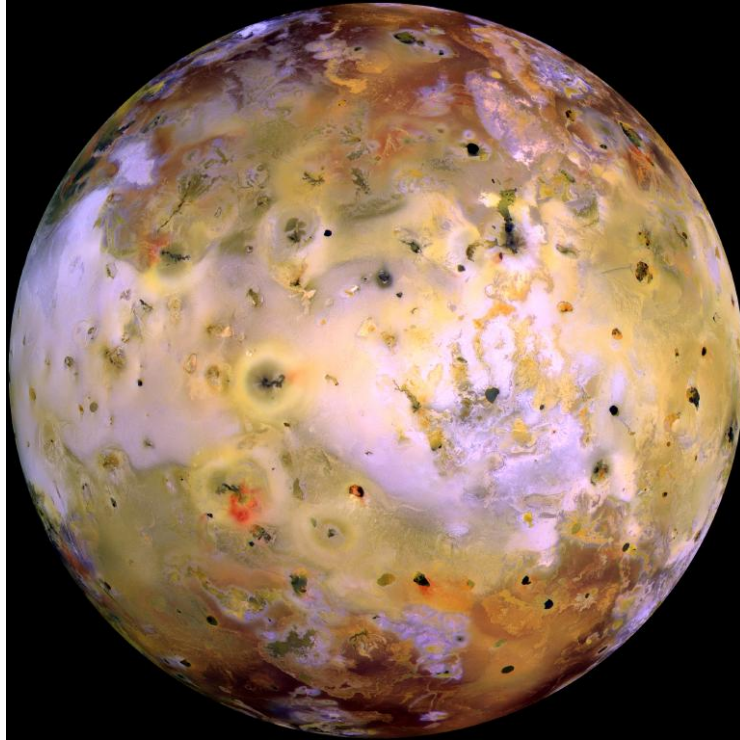
The discussion above focuses on the habitability, keeping the question of the possible origin of life as a separate question. Asking this question for Europa is important not only to understand whether life ever existed there, but also to test our understanding of the origins of life on Earth. A major focus of astrobiological research seeks to understand how planetary environments may be geochemical precursors for life as we know it, while other work tests how life changes the system to match its needs. Both surface and deep ocean systems are described as possible locations for the origins of life on Earth—where surface pools of water where hydration, dehydration, and the possible introduction of exogenic or endogenic materials generate the conditions for life, or where hydrothermal vents in an anoxic ocean set up energetic reactions that could build precursor geochemical systems. An origin of life on Europa, at such a great distance from Earth, likely would represent the chance to address, in part, this debate about life's origins on Earth and the necessary types of systems for life to arise.

Even if Europa is presently uninhabitable, or uninhabited, it may well be that the moon once was a stable place for life. Unique from places such as Mars where the origin of life would likely have had to happen early, Europa may have been continuously habitable for the lifetime of the solar system. Might there be an evolved community within or beneath the ice? The determination of habitability gets us a step closer to answering this question, and life detection at Europa would truly change the way we think about astrobiology, planetary science, and even life on Earth.

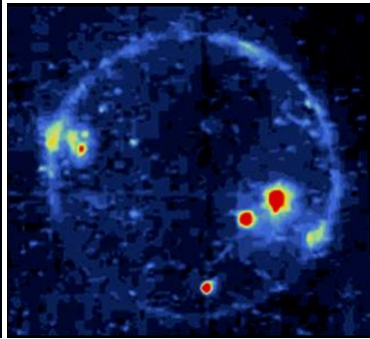
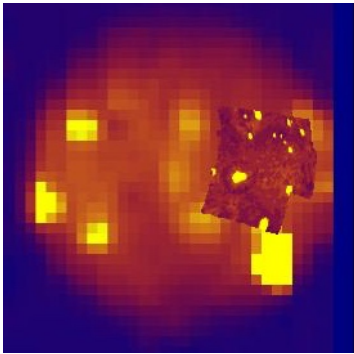
[Q6, Q10]

5.4 Io Science Objectives

Io is key to understanding tidal heating, including of ocean worlds. These bodies would not be geologically active without tidal heating, a theoretical process that was confirmed by observations of Io. Io remains the solar system object with the clearest expression of tidal heating: highly active volcanoes, and more than on any other world, including Earth. Due to its proximity to Jupiter, tidal heating affects Io more than any other world, but the process is not completely understood. Ionian eruptions not only affect Io's surface, but also its atmosphere and the Jovian environment, especially the magnetosphere.



1. What are the processes that control Io's volcanic eruptions and how do they vary spatially and temporally?



Over one hundred active volcanic centers have been identified, yet the formation of the volcanoes, the style and duration of eruptions and connectivity between volcanic centers are poorly understood. We do not yet know the composition of Ionian volcanoes or if the eruption type at a single location changes with time. Minor volcanic types

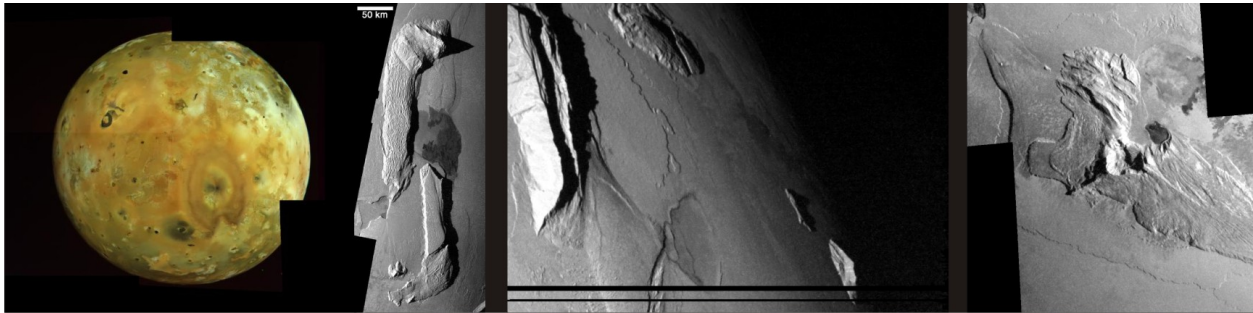
dominated by sulfur or SO_2 have been suggested, but their extent is unknown. Io's volcanoes may be similar in composition to many on Earth and understanding how this process works in relative isolation on Io will inform how volcanoes work in the more complicated system on Earth. The high-volume volcanism and outgassing that can be observed in action on Io are also key components of the evolution of all of the terrestrial planets.

Some estimated lava temperatures may require ultramafic compositions. Ultramafic volcanism was common in the early histories of the Earth, Moon, Mercury, Mars, and perhaps Venus, but Io is the only location where we may be able to observe such volcanism in action. Io also features active flood lava eruptions, with a wide range of eruption rates ($<10^3$ to $>10^6 \text{ m}^3 \text{ s}^{-1}$). Several large pulses in flood lava volcanism on Earth are precisely coincident with Phanerozoic mass extinctions, but establishing a causal linkage is hampered by lack of observations of active effusive

eruptions of this scale. Again, Io is the only place in our Solar System where we can directly observe such eruptions.

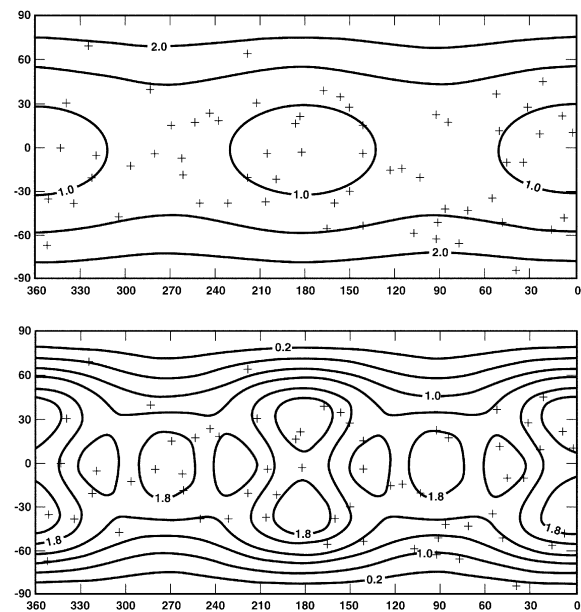
[Q2, Q3, Q7, Q10]

2. What processes form Io's mountains and what are the implications for tectonics under rapid resurfacing and high heat-flow conditions?



There are more than 100 mountains on Io, the majority appearing to be tectonic, rather than volcanic, structures. There is no obvious global pattern to their locations; with the exception of a bimodal distribution with longitude. While mountains have local associations with paterae (volcano-tectonic depressions), globally there is no correlation and perhaps an anti-correlation. The most favored model for mountain formation since the Galileo era invokes compressive stresses in the lithosphere induced by rapid volcanic resurfacing. The details of the mountain formation process and the relationship of this process to Io's volcanism, and in particular the formation of paterae, have yet to be discovered. These studies can reveal more about Io's crustal properties and evolution and transfer of internal heat and similar mountain-building processes on other planets.

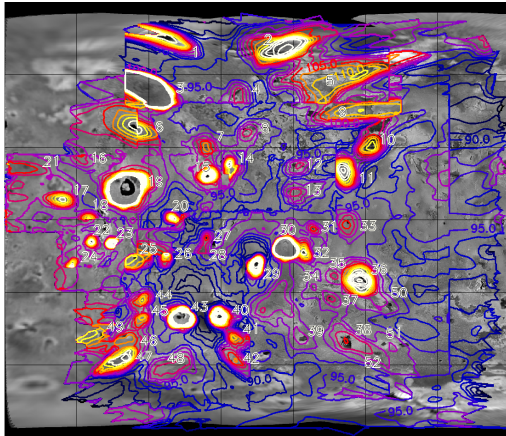
[Q3, Q7, Q10]



3. What are the magnitude, spatial distribution, temporal variability, and dissipation mechanisms of tidal heating within Io? How is heat transfer to the surface controlled by internal structure and what are the properties of that structure?

Io's extremely active volcanism is caused by excessive amounts of internal tidal heating, but we still do not understand the details of the tidal heating process. Understanding the process on Io, where its signature is strongest, will help us to understand how this fundamental process operates in our solar system and beyond. Gravity science is needed to measure Io's tides, as well as new

astrometric measurements to measure Io's orbital evolution, and geodesy to determine Io's exact shape and orbital motions such as libration.

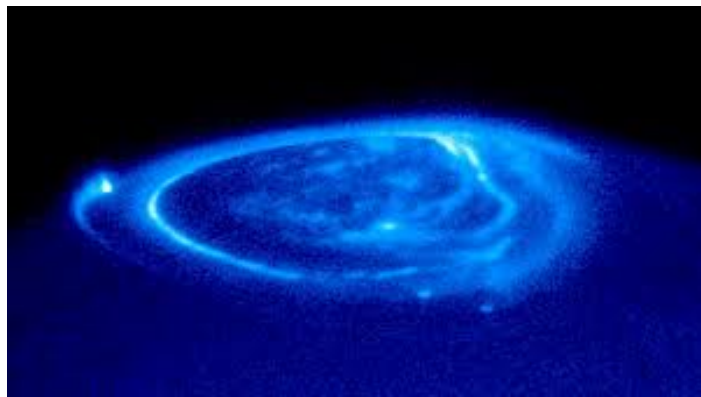
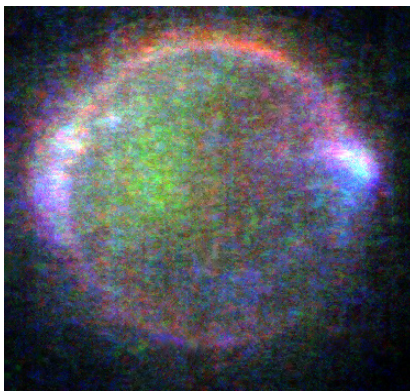


Measurements of Io's heat flow from ground-based telescopes and spacecraft data are $\sim 2 \text{ W/m}^2$, more than twice as large as the upper limit expected from models of steady-state tidal heating over geologic time, yet how this has affected Io's interior and surface is still unknown. Comparisons of the spatial variability in Io's volcanic constructs to predictions from tidal heating models show they are more consistent with the heating occurring in the asthenosphere rather than the deep mantle, although both regions may be heated. Magnetometer data from Galileo suggest the presence of an interior "magma ocean" or globally interconnected partial melt, yet how large or deep this magma reservoir

is and how it is maintained under a density inversion has not yet been determined. The temporal variability of heat flow and volcanic output are not well known, and studies can reveal how tidal heat is transferred to the surface. Tidal heating is the major contributor to active surface geology in the outer Solar System, so studies of hyperactive Io are essential to furthering our understanding of tidal heating in general.

[Q2, Q6, Q7, Q10]

4. How do the density and composition of Io's atmosphere vary temporally and spatially, what controls the variability, and how is the atmosphere affected by changes in volcanic activity? How is the surface (composition and structure) affected by the atmosphere?



Aurorae on Io (left) and Jupiter (right), including the Io footprint.

Io's atmosphere appears to be controlled by both volcanic emissions from Io's near-surface and deep interior and sublimation of surface volatiles. Recent observations suggest that, while volcanoes are the source of the atmospheric volatiles, sunlight controls the atmospheric pressure on a daily basis. More data are necessary to determine if this varies with time and compositional changes.

[Q2, Q6, Q7, Q10]

- 5. How do material and energy flow within and between the Io torus and Jupiter's magnetosphere and how does that change with time? Is Io's magnetospherically-driven volatile loss an archetype for similar volatile loss processes that may have been important elsewhere in the solar system and beyond? How does Io's atmosphere affect the state of the Io torus, the Jovian magnetosphere, and aurorae?**

As material escapes from Io's low gravity, it forms a vast neutral cloud. The Io Torus, which extends around Jupiter in Io's orbit, is a ring of plasma also created from Iogenic material. The coupling between these plasma populations is a fundamental and unresolved problem in space physics. The interactions between Io's volcanoes, atmosphere, neutral cloud, and torus are complex and have implications for the entire Jovian system and beyond.

[Q2, Q6, Q7, Q10]

5.5 Enceladus Science Objectives

Despite its size (500 km in diameter), diminutive Enceladus has emerged as one of the most compelling targets for planetary exploration. Powered through its gravitational resonance with neighboring Dione, Enceladus maintains vigorous activity at its south pole, including active tectonics, high heat flow, and most importantly, ongoing venting of plume gases and icy particles that betray a rich chemistry indicative of a subsurface sea.

- 1. *Enceladus' Interior.* What is the nature of Enceladus' interior? That is, what is the size and shape of its rocky core, the thickness of its icy crust as a function of location, and what is the thickness and extent of its subsurface ocean or sea?**

A gravity model of Enceladus, constructed using long-range data collected by the Cassini spacecraft, was initially interpreted to indicate a large mass anomaly at the moon's south pole indicative of a large, regional subsurface sea. However, the gravity data were re-interpreted, including a higher-order rotational correction, to be indicative of a widespread, perhaps global ocean. More recently, Cassini imaging data were used to determine Enceladus' precise rotation state and thereby derive the physical libration of the body. The results were found to be consistent with a global subsurface ocean rather than a local sea, with a thinner ice shell at the south polar region than elsewhere.

Remaining questions include: How uniform is the ice shell thickness? What are the various contributions from thickness and density (salinity, clathrates, porosity) variations? If Enceladus' core is low density, is it porous, and is there internal hydrological circulation? All of these questions feed into something more fundamental regarding Enceladus' origin. Is Enceladus an original regular satellite, as is usually assumed, or was it born from a massive mega-ring during a later epoch, as has been proposed by some research?

[Q1, Q2, Q10]

2. *Composition of Enceladus' Ocean.*

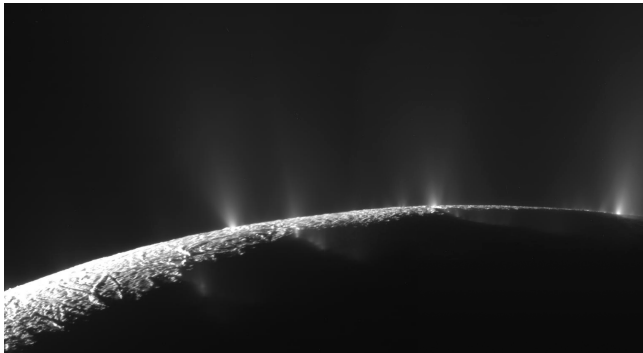
Recent *in situ* Cassini data have informed our understanding of the nature of the ocean composition. Sodium and potassium salts have been observed in the Enceladus plume, indicating that the plumes originated in a salt-water reservoir that is, or has been, in contact with rock. Nanometer-sized silica particles, whose composition and size range indicate high-temperature (>90°C) hydrothermal reactions are associated with geothermal activity, have been detected by the Cassini Cosmic Dust Analyser instrument. This activity is able to transport hydrothermal products from the ocean floor at least 40 km up to the surface through the Enceladus plume. Furthermore, Cassini Ion and Neutral Mass Spectrometer (INMS) data indicate H₂ in the Enceladus plume (at levels of 0.4-1.4% by volume); pointing to water-rock interactions as the most likely source - the first evidence of ongoing hydrothermal activity beyond Earth.

Remaining questions regarding Enceladus' ocean include: Are ammonia, methanol, chloride or bicarbonate salts, or some other materials, depressing the melting point and enabling a liquid water layer or changing rheological properties within Enceladus' solid ice shell? What are the global characteristics of the ocean, in terms of temperature, oxidation state, pH, and Eh? What does ocean chemistry imply for Enceladus' origin and evolution? Are the organics inferred from Cassini plume data primordial or a product of synthesis within Enceladus, either currently or in the past?

[Q1, Q3, Q4, Q10]

3. *Enceladus' Plumes. How do the mechanics of Enceladus' erupting plumes actually work? What are the roles and importance of tidal and endogenic stresses (that is, those due to convection, diapirism, freezing and melting of the sea/ocean)?*

How does the liquid water reservoir communicate with the surface?



What are the physical and chemical conditions in the plumes? What are the plume characteristics, particle masses, size and velocity distributions? How long-lived are the plumes? Does plume production vary in time? Are plumes cyclic, episodic? Do source regions migrate along the tiger stripes?

Were other regions on Enceladus cryovolcanically active in the past (or even active today at a low level)? And how does

plume fallout affect Enceladus' surface? How do the plumes feed the E ring? What are the escape and resurfacing rates?

[Q10]

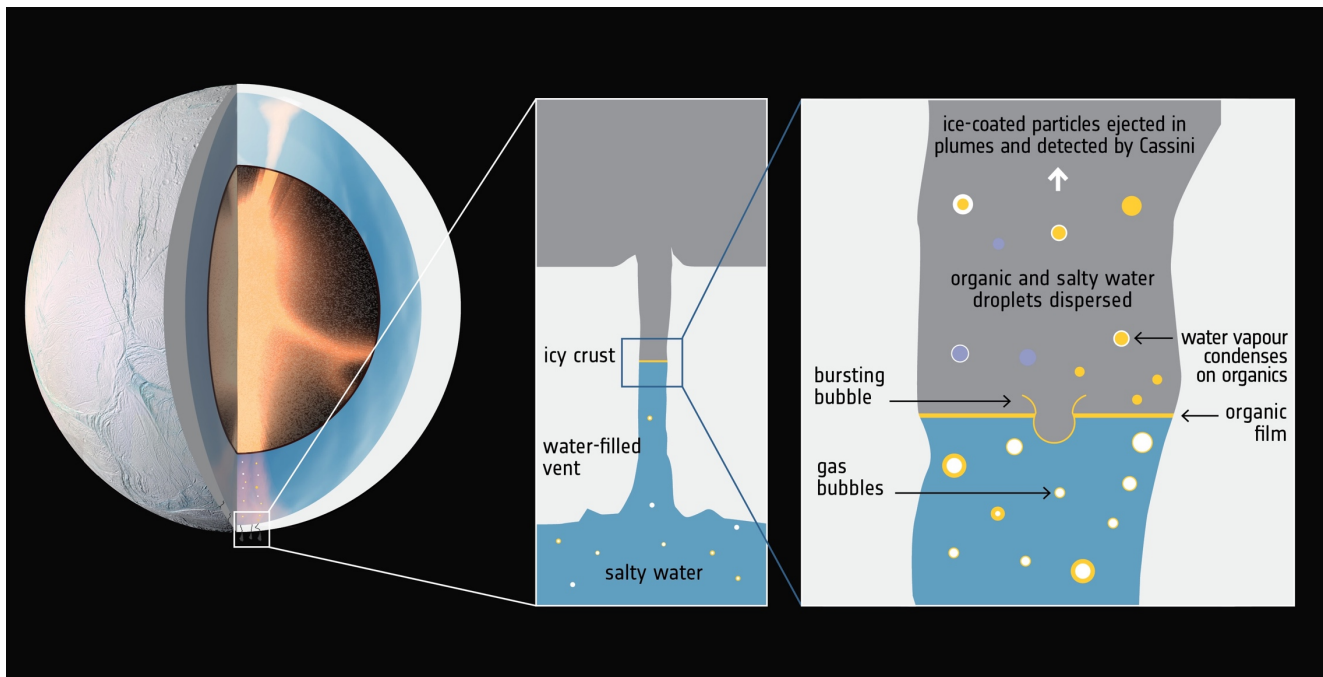
4. *Enceladus' Tidal Energy. Where is the tidal energy that powers Enceladus' activity actually deposited? What is the balance between anelastic dissipation in the solid ice shell, frictional dissipation on faults in the icy lithosphere, and oceanic dissipation? Moreover, how has this varied in the geological past and across different terrains? Under what circumstances could there be or have been substantial tidal dissipation in the rocky core?*

What is Enceladus' heat flow and how is that heat flow distributed? How is that heat flow stored (if it is) and transported? A related question is how long can a liquid ocean exist on Enceladus?

How large are the tidal stresses, and how much tidal deformation occurs? What is the nature of the tectonic features on Enceladus? Why do tectonic expression and patterns vary across the surface? To what extent is the active tectonics on Enceladus a model for geologically recent tectonics on Europa and older tectonized terrains on Ganymede and other icy satellites?

[Q10]

5. Enceladus' Habitability. Is Enceladus' subsurface sea habitable? What do the answers to the above questions imply for conditions in the geological past to have been conducive to the origin and evolution of life.



We know there is 'CHON' (carbon, hydrogen, oxygen and nitrogen) on Enceladus, but is there 'CHONPS,' and are other elements bioavailable? What energy sources are potentially available for life? And what lessons from Enceladus apply to Europa, and vice-versa?[Q6]

6. Search for Life in Enceladus. Is there extant life within Enceladus?

Enceladus' plume contains water, organics, and salts and minerals that are indicative of water/rock interactions in alkaline hydrothermal vents. These are many of the components—internal heat, an extensive liquid-water ocean, organics, and geochemical cycling—necessary to support an extant biosphere. This motivates the search for evidence of life in the ocean through the analysis of plume materials either in situ or in samples returned to Earth. Questions: Are there biological building blocks (e.g., amino acids; lipids) in the Enceladus ocean? Are the distributions of those building blocks consistent with biotic or abiotic sources? Is the organic composition of the ocean reminiscent of a prebiotic world, or is it consistent with the emergence and evolution of life?

[Q6]

5.6 Titan Science Objectives

Titan, the largest satellite of Saturn, larger than the planet Mercury, shares more ongoing physical processes with Earth than any other planetary body. It possesses a nitrogen-based atmosphere more massive than our own, with several percent methane resulting in unique and complex atmospheric chemistry and an organic-dominated surface. Active rainfall, erosion, and aeolian processes create rivers, lakes, seas, eroded landscapes, and vast fields of sand dunes. The Titan environment is rich with complex organic molecules that inform studies of prebiotic chemical evolution, and its climate has many analog processes to those on Earth, such as air-sea exchange, moist convection, seasonal polar vortices, and greenhouse and anti-greenhouse effects. Underlying all this is a Ganymede-sized icy satellite with a deep internal ocean of liquid water.

Goal 1: Explore surface, atmospheric, and interior processes

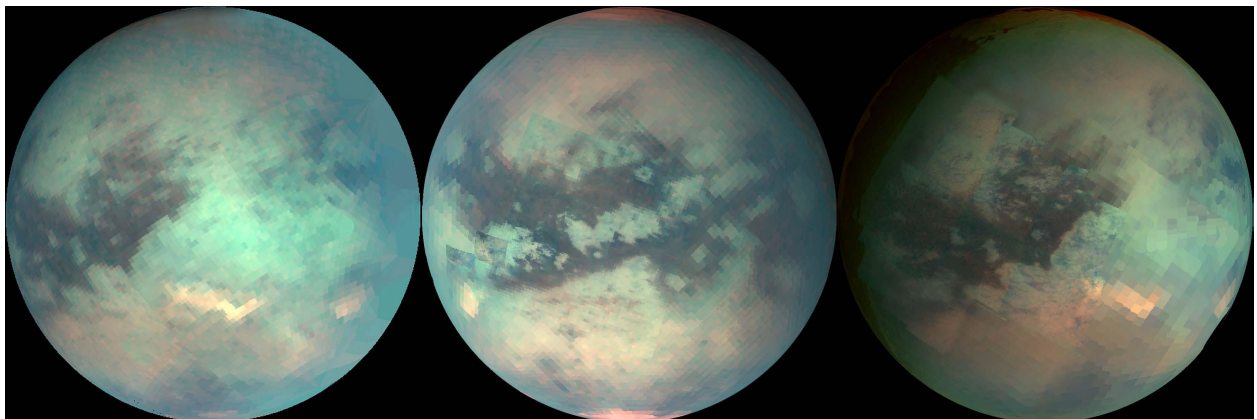
Explore the processes currently affecting the surface, atmosphere, and interior of Titan and how these processes are related to Titan's history and composition, as well as similar processes on Earth and other solar and extrasolar planets.

Goal 2: Investigate change in the atmosphere and surface

Investigate how and where change occurs on Titan today as a result of orbital and internal variations, and how large-scale climatic and evolutionary changes have affected Titan over its geologic past, as a means to help us understand similar processes and activities on Earth and other planetary bodies.

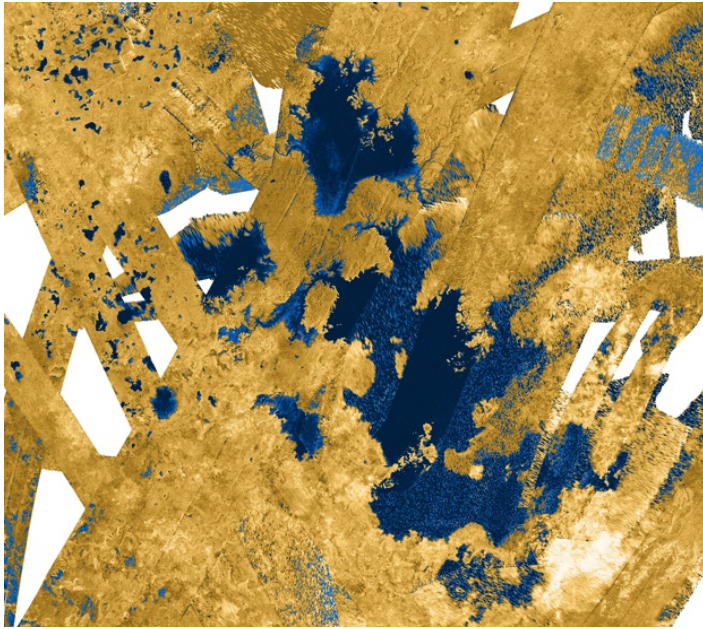
Goal 3: Determine habitability and explore the limits of life

Investigate both of Titan's liquid reservoirs --- hydrocarbons on the surface in lakes and seas and water in a deep subsurface ocean --- and determine if they have been amenable to the rise of life, or its molecular precursors.



1. What processes are active on Titan's surface and in the lithosphere and how have these processes, and the surface of Titan, changed over time?

Surface features that are the end result of extensive atmospheric interaction via erosion and internal energy such as rivers, lakes, mountain belts, dunes, and potential cryovolcanoes have been



observed on Titan. The evolutionary history of these features, and their current state and activity, is not clear, though the surface is relatively young as evidenced by the presence of only a handful of identified impact craters. The primary mode of resurfacing, whether by erosion, cryovolcanism or overturn, tectonism, or deposition from atmosphere-derived organics, or whether the primary mode has changed over time, is not yet determined. Erosion of the surface by methane and ethane fluids requires an interplay between the surface, interior and atmosphere. Exchange of volatiles from the interior to the atmosphere may occur via disruption of clathrates, which contain methane,

ethane and other noble gases in near-surface and interior ices, though how frequently and where this occurs is not known.

[Q2, Q7, Q10]

2. How and when do changes in Titan's atmosphere occur, and how are these expressed at the surface?

Seasonal and longer-term changes are thought to occur in Titan's atmosphere, based on observations, studies of orbital parameters, surface morphologies, and upper atmospheric chemistry. Titan's orbit requires it to undergo shorter and more severe southern and longer and more subtle northern summers, which has likely led to the observed presence of vast lakes and seas in the northern hemisphere. Solar cycles have an effect on the methanological cycle in the upper atmosphere, which affects the overall atmospheric dynamics and deposition of materials on the surface. The methane cycle also affects atmospheric flow and can be observed as changes in clouds and precipitation. Long-term changes likely cause rising/falling lake levels, modifications to dune fields and wind streaks, and regional climate change. The dynamics of Titan's atmosphere can be compared with those of Earth, Venus and Mars and mutually inform their evolution.

[Q2, Q3, Q7, Q10]

3. What was the thermal evolutionary history of Titan, and how was/is thermal activity expressed at the surface?

Based on moment of inertia measurements, Titan appears to have a low degree of differentiation. Given its size and young surface, more internal differentiation might be expected. There could be more differentiation while maintaining the observed moment of inertia if the silicate mantle were

in a state of hydration. Studies of the mode and amount of release of internal heat would inform the amount of internal differentiation as well as the amount of energy available for tectonism and volcanism. In addition, understanding the release of volatiles from the interior, such as ammonia and methane, is key to understanding differentiation and volcanism. Studies of tectonism and volcanism on Titan also help us understand the communication between the liquid water ocean at 50-100 km depth below the ice lithosphere and the organic-rich surface, which has astrobiological implications.

[Q2, Q3, Q7, Q10]

4. What processes occur in Titan's atmosphere and on the surface that lead to the formation of organic molecules, and could these materials undergo prebiotic and biotic processes?

Photodissociation of methane high in Titan's atmosphere leads to the formation of long-chain organic (C-H based) molecules. Cassini has detected an impressive variety of species including ethane, hydrogen cyanide, propane, butane, acetylene, and many other higher-mass hydrocarbon and nitrile compositions. However, details (e.g., the ion neutral chemistry, the effects of lower atmosphere radical chemistry, the effects of coagulation and condensation processes, and how abundant they are and the degree of the incorporation of nitrogen) and how far Titan's organics may have progressed toward prebiotic chemistry have yet to be determined. Oxygen from Enceladus or incorporated from liquid water has the potential to form amino acids. Organic molecules in Titan's lakes, beaches, and rivers, in transient surface liquid water, or in the interior ocean have the potential for prebiotic and biotic processes, placing fundamental constraints on the circumstances, chemistry, and timescale for the formation of life.

[Q2, Q6, Q7, Q10]

5. How can Titan inform us about extrasolar planets, Mars, and Earth?

An extrasolar planet similar to Titan in size and effective temperature would orbit a typical M-dwarf star at around 1 AU – far outside such stars' habitable zones where tidal locking, coronal mass ejections, flares, and inefficiency in volatile delivery during formation affect planetary evolution. Around the smallest M-dwarfs, this distance would shrink to 0.2 AU, but even were we to disregard these cases, the number of remaining M-dwarfs vastly outnumbers G-dwarfs like the Sun, leading to a high probability of finding Titan-like bodies in the galaxy. Because the 1 AU environment around M-dwarfs is benign, in the same sense as is that of our Sun, planets at that distance from an M-dwarf should have stable methane hydrologic cycles for which our own Titan can be a good guide.

Titan's geological and atmospheric processes have many analogs to those on Earth and Mars, as well as Venus, including aeolian and fluvial surface erosion, transport, and deposition, air-sea exchange, moist convection, seasonal polar vortices, and greenhouse and antigreenhouse effects. Titan's rich organic chemistry informs studies of prebiotic chemical evolution on Earth.

[3, 9, 10]

5.6 Triton Science Objectives

Neptune's moon Triton has only been briefly studied by one spacecraft. Voyager flew by in southern summer and imaged just one side of Triton at moderate resolution. Triton's youthful

surface has unique geological features. Its nitrogen atmosphere is in vapor pressure equilibrium with surface frost. Remarkable plumes jet up to 8 km from the surface.

1. Interior Structure. What is the nature and history of Triton's interior structure? Does Triton have a subsurface liquid ocean? Does Triton have a current or past dynamo magnetic field? What is the current heat flow?

If Triton was captured early in the history of the Solar System, then tidal evolution to a circular orbit and differentiation may have been completed within several 10^8 years, followed by billions of years of impact cratering. Yet the surface is lightly cratered. New models of obliquity evolution suggest that modest tidal heating is ongoing. Can radiogenic *and* tidal heating today cause convection in a subsurface layer that erases craters and/or otherwise renews the surface? Is a metallic inner core dynamo possible?

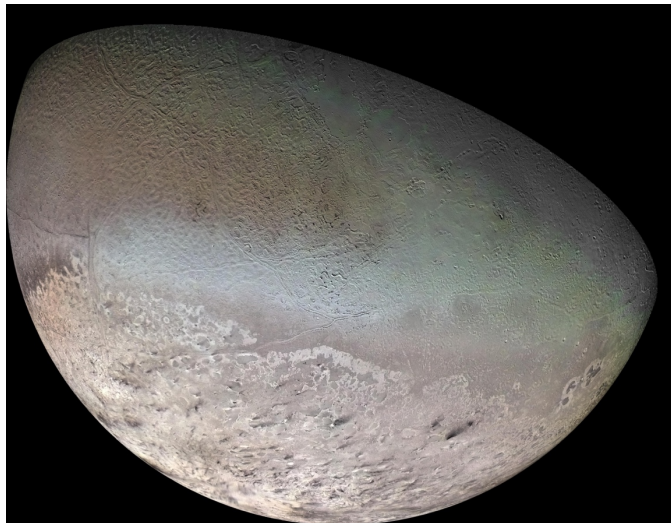
Subsurface oceans may be a common feature of icy moons, and Triton's young surface age (<100 Myr, possibly <10 Myr) may be indicative that it too has a subsurface ocean. If Triton possesses an internal ocean, is it 'perched' above high-density ice (perhaps like Ganymede) or in contact with the rock core (like Europa)?

If Triton collided with existing moons in orbit around Neptune during its capture, its composition could be a mix of planetocentric and heliocentric material. Is Triton still colliding with planetocentric debris?

[Q1, Q2, Q3, Q10]

2. Surface geology. What are the geologic processes responsible for Triton's unique surface features? What is the global cratering record on Triton? Has cryovolcanism played a major role in renewing the surface? Is diapirism responsible for Triton's enigmatic cantaloupe terrain? How spatially homogeneous is Triton's surface, or, put differently, what undiscovered geologic features lie in regions that were not well-imaged by Voyager?

Triton's surface age of <10 - 100 Myr is derived from the sparse number of craters on its surface. Triton's young surface with relatively few craters stands out among moons in the solar system and puts it in a class with Io, Europa, Titan, and parts of Enceladus and Pluto – other moons with active geologic processes today.



What is the range of ages of Triton's surface units? We need a global data set to fill in Voyager's limited surface coverage and spatial resolution.

Many landforms on Triton are unique in our solar system (e.g., cantaloupe terrain) – how are they formed? What is the global distribution of geological terrains? What remains to be discovered? And how does the interaction of tidal dissipation, heat transfer, tectonics, cryovolcanism/diapirism, and surface-atmosphere interactions drive resurfacing of Triton?

[Q10]

3. *Surface composition and atmosphere.* What does Triton’s surface chemistry tell us about its origin? Is oceanic chemistry expressed on its surface? How are different composition ices partitioned across the surface? What is the nature of Triton’s global circulation and climatic response?

Changes in atmospheric pressure since the Voyager flyby have been detected in stellar occultations observed from Earth. Seasonal volatile migration is predicted, as Triton’s nitrogen atmosphere in vapor pressure equilibrium with surface ices responds to changes in insolation. How has seasonal volatile migration affected the south polar cap and atmosphere since Triton has gone from southern spring (Voyager) to summer? How much mass has been transferred into the atmosphere and northern polar region? The compositions of Triton’s individual surface units are unknown because Voyager did not have a way to determine surface composition, and ground-based observations have limited spatial resolution. Volatile ice migration is expected from climate models – which ices are where when? How does the seasonal sublimation and migration of volatiles into and out of the atmosphere drive winds? How do volatile inventories compare between Triton and Pluto and other dwarf planets of the transneptunian region?

[Q9]

4. *Triton’s plumes.* What is the source of Triton’s plumes? Are Triton’s plumes a result of solar-driven activity (like Mars)? Or are they endogenic (like Enceladus)?

What do the sites and timings of plume occurrence tell us about the energetics, relevant processes, and the nitrogen reservoir? Is there a true polar cap? If solar-driven, similar activity may also be occurring on Mars, and Triton may prove to be a wellspring of information about this unearthly phenomenon. If endogenic the plumes may be sampling a subsurface material and possibly a subsurface ocean. Similar arguments apply to recent cryovolcanism. These would be important for understanding Triton’s internal heat flow and tectonics, and would add Triton to the list of key astrobiological targets.

[Q6]

5. *Triton’s interaction with Neptune’s magnetosphere.* How does the highly conducting Triton ionosphere interact with the corotating magnetosphere of Neptune? How is Triton’s extremely strong ionosphere generated and maintained, and are magnetospheric interactions key? Does an induction signal tell of an interior ocean?

How is the relatively dense neutral torus of Triton formed, and what is its relationship to loss processes from Triton’s atmosphere? Voyager radio science observations revealed a significant ionosphere with a well-defined peak at ~350 km altitude; however, the distance and the geometry

of the Triton closest approach precluded in situ observations of either the ionosphere or its interaction with Neptune's magnetosphere. Neptune's magnetic field has a large tilt, so (like in the Jupiter-Europa system) an induced magnetic field should exist if Triton contains a conductive subsurface ocean.

[Q10]

6.0 PLANETS IN THE KUIPER BELT

The three large KBOs Pluto, Charon and Triton (as a probable captured KBO) observed close up so far show a tremendous diversity of surface features and atmospheric phenomena. (Note: Triton is discussed elsewhere in this document.) The 2015 *New Horizons* flyby of Pluto and Charon revealed details about the geology, surface composition and atmospheres of these worlds with resolutions as fine as ~80 m/pixel. A large variety of surface features were revealed especially on Pluto, including a large basin filled with nitrogen-dominated glacial ices that appear to be undergoing convection. Much of the landscape surrounding this basin (Sputnik Planitia) appears to have been carved by glacial valleys. Surfaces ranging from uncratered to heavily cratered were observed indicating that Pluto has been active over much of Solar System history. Maps of Pluto's surface composition show latitudinal banding, with non-volatile material dominating the equatorial region and volatile ices at mid- and polar latitudes. This pattern is driven by the seasonal (and possibly Milankovitch-scale) cycles of solar insolation. The temperature of Pluto's upper atmosphere was found to be much cooler than previously modeled. Images of forward-scattered sunlight revealed numerous haze layers extending up to 200 km from the surface. Charon was found to be currently inactive, but nearly 4 billion years ago it experienced major extensional tectonism and resurfacing (probably cryovolcanic). Charon was also found to have thin deposits of reddish organic materials at its poles that were originally derived from CH₄ escaping Pluto. These discoveries have transformed our understanding of icy KBO planets in the outer Solar System, demonstrating that even at great distances from the Sun, worlds can have active, and even ongoing, geologic and atmospheric processes.

Other KBO planets are likely to be diverse as well (Table 6.0-1).

Table 6.0-1 KBO Planets

Known KBOs Larger Than 900 km Diameter						
Name	Diameter (km)	Perihelion/Aphelion (AU)	Current distance from Sun (AU)	Surface characteristics	Other observations/hypotheses	Moons
Eris	~2326 (Sicardy et al., 2011)	P=38 A=98	96	Appears almost white, albedo of 0.96 (Sicardy et al., 2011), higher than any other large Solar System body except Enceladus. Methane ice appears to be quite evenly spread over the surface (Brown et al., 2005; Licandro et al., 2006).	Largest KBO by mass (Brown and Schaller, 2007), second by size. Models of internal radioactive decay indicate that a subsurface water ocean may be stable (Hussmann et al., 2006). May have N ₂ convecting layer.	Dysnomia (Brown et al., 2006)
Haumea	~1600 (Lockwood et al., 2014; Ortiz et al., 2017)	P=35 A=51	51	Displays a white surface with an albedo of 0.6-0.8 (Rabinowitz et al., 2006), and a large, dark red area (Lacerda et al., 2008; Lacerda, 2009). Surface shows the presence of crystalline water ice (66%-80%) (Trujillo et al., 2007), but no methane, and may have undergone resurfacing in the last 10 Myr. Hydrogen cyanide, phyllosilicate clays, and inorganic cyanide salts may be present (Chadwick et al., 2007), but organics	Is a triaxial ellipsoid, with its major axis twice as long as the minor. Rapid rotation (~4 hrs), high density, and high albedo may be the result of a giant collision (Brown et al., 2007). Has the only ring system known for a TNO (Ortiz et al., 2017).	Hi'iaka and Namaka (Brown et al., 2005; Ragozzine et al., 2008; Fabrycky et al., 2008).

				are no more than 8% (Pinilla-Alonso et al., 2009).		
2007 OR ₁₀	~1535 (Pál et al., 2016)	P=33 A=101	87	Amongst the reddest objects known, perhaps due to the abundant presence of methane frosts (tholins?) across the surface (Brown et al., 2011). Surface also shows the presence of water ice.	May retain a thin methane atmosphere (Brown et al., 2011).	S/(225088) 1 (Kiss et al., 2017).
Makemake	~1427 (Brown, 2013)	P=39 A=53	52	Methane, ethane, tholins, and possibly nitrogen present on the surface (Brown et al., 2007). Smaller amounts of ethylene, acetylene, and high-mass alkanes (like propane) may be present (Brown et al., 2015). Appears red in the visible spectrum (Licandro et al., 2006). Some nitrogen present, but much less than on Pluto or Triton (Tegler et al., 2008).	May have an atmosphere up to 4-12 nanobar at surface (Ortiz et al., 2012). May have N ₂ convecting layer.	MK 2 (Parker et al., 2016)
Quaoar	~1092 (Braga-Ribas et al., 2013; Fornasier et al., 2013)	P=42 A=45	42	Surface is moderately red, and albedo may be as low as 0.1, maybe indicating that fresh ice has disappeared from its surface. Crystalline water ice exists at the surface. Small presence (5%) of methane and ethane ice (Schaller and Brown, 2007).	Crystalline water ice indicates that temperature rose to at least -160°C sometime in the last 10 Myr, leading to speculation that cryovolcanism may be occurring, spurred by internal radioactive decay (Jewitt and Luu, 2004).	Weywot (Brown and Fraser, 2010).
Sedna	~1030 (Pál et al., 2012)	P=76 A=936	86	Has an albedo of 0.32, a homogeneous surface in color and spectrum, and one of the reddest surfaces in the Solar System, perhaps caused by a surface coating of tholins (Trujillo et al., 2005). Surface composition upper limits are 60% for methane and 70% for water ice (Trujillo et al., 2005). 24% Triton-type tholins, 7% amorphous carbon, 10% nitrogen, 26% methanol, and 33% methane have been suggested for the surface composition (Barucci et al., 2005).	One of the most distant-known objects in the Solar System, with a highly eccentric orbit, leading to speculation that it may be a member of the inner Oort cloud (Brown et al., 2004), in addition to extra-solar origin hypotheses. Models of internal radioactive decay indicate that a subsurface ocean may be stable (Husmann et al., 2006).	None detected.
2002 MS ₄	934 (Vilenius et al., 2012)	P=36 A=48	47			None detected
Orcus	917 (Fornasier et al., 2013)	P=31 A=48	48	Has an albedo of 0.3, is gray in color, and is rich in crystalline water ice, mixed with tholins (de Bergh et al., 2005). Methane and ammonia may be present. Water and methane ices can cover no more than 50% and 30% of the surface respectively (Trujillo et al., 2005).	A plutino in a 2:3 resonance with Neptune. Crystalline water ice, and possible ammonia ice, may indicate surface renewal by cryovolcanism (Delsanti et al., 2010). Models of internal radioactive decay indicate that a subsurface ocean may be stable (Husmann et al., 2006).	Vanth (Brown et al., 2010)

1. Interior Structure. What is the nature and history of KBO planets' interior structures? What is the nature of potential subsurface liquid oceans?

New Horizons flyby data has allowed accurate determination of the sizes, shapes, and densities of Pluto and Charon, and has also revealed extensive evidence for large-scale resurfacing of them since their formation, supporting the hypothesis that both have experienced differentiation into a rocky core (2/3 and 3/5 by mass for Pluto and Charon respectively) and a water ice mantle. Enormous tectonic belts that straddle the encounter hemispheres of both worlds also suggest that they have harbored subsurface oceans at some time in their histories. The lack of evidence for geological activity on Charon since 4 billion years ago suggests that a subsurface ocean has not persisted to the present day, but it has been argued that reorientation of Sputnik Planitia on Pluto arising from tidal and rotational torques can explain the basin's present-day location, and that such reorientation requires a subsurface ocean to be feasible, which could survive to the present day with a suitably rigid, conductive water ice shell. A more general question is the extent to which the thermal evolution of the interiors of these planets has contributed to the wide variety of landforms at their surfaces (especially Pluto), including tectonism and potential cryovolcanism. A dedicated search for a Plutonian subsurface ocean should be a priority for any future mission to the Pluto system. The velocity and distance of the New Horizons flyby were such that it was not possible to measure or constrain the gravity field of either Pluto or Charon, meaning that such measurements could not be used to infer their moments-of-inertia. A Pluto orbiter would reach much closer to Pluto than New Horizons did, and would also perform several close flybys of Charon, allowing these measurements to be fulfilled for both KBO planets, and providing further constraints on their interior structures. Obviously detailed knowledge regarding the interiors of other KBO planets would similarly benefit from orbiter studies. Global topographic measurements will facilitate interpretation of the gravity field, determine the thickness of the upper ice shell, and constrain the depth of the putative subsurface ocean. Various KBO planets display somewhat similar sizes and densities (bulk compositions) to Pluto, meaning that they may share similar interior structures to Pluto, and subsurface oceans are potentially a common phenomenon amongst them. New Horizons did not carry a magnetometer, and it is unlikely that KBO planets possess magnetospheres, but to investigate this unresolved issue, organizers of future flagship missions may consider equipping them with a wider array of fields and particles experiments than what was carried by New Horizons (such as magnetometer). Detection of magnetic fields at these worlds will have major implications for their interior states.

[1, 4, 6, 10]

2. Surface geology. What are the geologic processes responsible for the unique surface features of Pluto and Charon? What are their global cratering records? To what extent has cryovolcanism renewed their surfaces? Are the surface geologies of Pluto and Charon typical of KBO planets in general?

The cratering record of Pluto's encounter hemisphere indicates a vast range of surface ages, encompassing very ancient, heavily cratered terrain such as the dark equatorial band informally named Cthulhu Macula that has changed little since the heavy bombardment, as well as extremely young landscapes, most obviously the craterless (at available resolution) nitrogen ice plains of Sputnik Planitia, which are experiencing ongoing surface renewal. This wide range of surface ages is reflected in the great diversity of distinct terrains seen within the encounter hemisphere, implying a complex geological history that has been influenced by both endogenic and exogenic energy sources (including internal heating and insolation/climatic effects).



Despite this quantum leap in our understanding of these KBO planets, investigation of the geologies of Pluto and Charon is hindered by our incomplete views of their surfaces. New Horizons imaged ~50% of each of Pluto and Charon at pixel scales ranging from 76 to 890 m/pixel (for Pluto) and 160 to 890 m/pixel (for Charon), with imaging of the opposite hemispheres ranging from a few kilometers to tens of kilometers per pixel. Surfaces south of 30°S were in darkness during flyby. Given that the geologies of these worlds vary substantially across even small lateral distances (especially for Pluto), mapping their entire surfaces at high resolution is essential to comprehensively answer questions that remain about the global distribution of geological terrains (some of which may have yet to be discovered), their relative ages, and how they have been shaped by specific combinations of internal heating, surface-atmosphere interactions, and compositional suites. Of particular interest are the highly unusual edifices on Pluto informally named Wright and Piccard Montes, which are hypothesized to be massive cryovolcanic constructs, and are unique within the outer solar system. Confirmation of whether these features are genuinely volcanic, or instead arose through some other geologic process, must be a specific objective of any future mission to the Pluto system. There is good reason to suspect that there are time-variable phenomena on Pluto (and presumably other large KBO planets), which would be ideal observations for orbital studies. We already know that other KBO planets display a wide variety of surface compositions, albedos, densities, and rotational lightcurves. Obviously detailed knowledge regarding the geology of other KBO planets would benefit from orbiter studies. However, first-order knowledge regarding the geology of other KBO planets could be obtained by flyby encounters, if that were the only option. Future KBO planet missions should also search and examine moons and rings around their targets.

[10]

3. Surface composition and atmosphere. What do the surface chemistries of Pluto and Charon tell us about their origins and geological processes? How are different ice compositions distributed across their surfaces? What is the history of climate change on Pluto and how has it manifested itself in Pluto's surface geology? Do other KBO planets share similar

surface compositions to Pluto and Charon, and what is the detailed nature of their possible atmospheres?

As with the panchromatic imaging of Pluto and Charon, high-resolution compositional and spectral maps resulting from the flyby are limited to their encounter hemispheres. These maps have allowed us to gauge surface compositions at a regional scale, but cannot resolve the compositions of features at a scale of less than several kilometers. Mapping surface composition in detail across the entire illuminated portions of their surfaces is a crucial step towards a full understanding of the geological histories of these KBO planets, especially for intricate landforms such as the “bladed terrain” named Tartarus Dorsa on Pluto, where surface composition can change markedly across small lateral distances. The New Horizons radio experiment, ultraviolet spectrograph, and other cameras provided detailed information on the structure, composition, and temperature of Pluto’s atmosphere, as well as its escape rate. Unresolved questions remain, however, including whether the observed haze layers are consistent with transport by winds, and if the atmosphere conditions can support cloud formation. More broadly, the history of climate change on Pluto is an issue of prime importance, in particular with respect to its effect on Pluto’s surface geology and what materials and phases are stable at what times in Pluto’s obliquity- and orbit-driven climate cycles.

Like Pluto, the surfaces of several KBO planets are known to display regions of high albedo. Eris has an albedo of 0.96, the highest of any other large body in the solar system except Enceladus. It is therefore likely that these KBO planets also harbor bright, exotic ices such as nitrogen and methane, and they will almost certainly play a major role in whatever geological processes characterize their surfaces. While sublimation and recondensation of volatile ices has greatly influenced Pluto’s geology, sublimation will be less efficient for very distant KBO planets due to the reduced energy environment, although there remains the potential for atmospheres around them to be sustained by such a process. Future missions to KBO planets should carry instrumentation appropriate for the detection of these ice species, as well as putative atmospheres. Earth-based telescopic observations can also continue to make new discoveries.

[4, 9, 10]

7.0 OCEAN WORLDS AND THE SEARCH FOR LIFE

7.1 Ocean Worlds: Understanding Oceans and Habitability

The Roadmaps to Ocean Worlds group defines an “ocean world” as a body with a current liquid ocean (not necessarily global). This definition focuses the Ocean Worlds studies to mainly outer solar system bodies – usually moons, though KBO planets are included. In considering ocean worlds, there are several with confirmed oceans, several candidates that exhibit hints of possible oceans, and worlds in our Solar System that may theoretically harbor oceans but about which not enough is currently known to determine whether an ocean exists. In the ROW Goals document, the philosophy is that it is critical to consider all of these worlds in order to understand the origin and development of oceans and life in different worlds: does life originate and take hold in some ocean worlds and not others, and why? Thus, it is important to study the full spectrum of ocean worlds. The Roadmap to Ocean Worlds is organized around four goals (Table 3).

Table 7.0-1. ROW Goals and examples of driving science questions within them.

ROW Goal	Select Driving Science Questions
ROW-1 Identify Ocean Worlds	Is there a sufficient energy source to support a persistent ocean? Are signatures of ongoing geologic activity (or current liquids) detected? How do materials behave under conditions relevant to any particular target body?
ROW-2 Characterize Oceans	What are the physical properties of the ocean and outer ice shell? How does the ocean interface with the ice shell and seafloor?
ROW-3 Assess Habitability	What is the availability (type and magnitude/flux) of energy sources suitable for life, how does it vary throughout the ocean and time, and what processes control that distribution? What is the availability (chemical form and abundance) of the biogenic elements, how does it vary throughout the ocean and time, and what processes control that distribution?
ROW-4 Search for Life	What are the potential biomarkers in each habitable niche? <u>How</u> to search for and analyze data in different environments?

Enceladus, Europa, Titan, Ganymede and Callisto have known subsurface oceans, as determined from geophysical measurements by the *Galileo* and *Cassini* spacecraft. These are *confirmed* ocean worlds. Europa and Enceladus stand out as ocean worlds with evidence for communication between the ocean and the surface, as well as the potential for interactions between the oceans and a rocky seafloor, important for habitability considerations. The subsurface oceans of Titan, Ganymede and Callisto are expected to be covered by relatively thick ice shells, making exchange processes with the surface more difficult, and with no obvious surface evidence of the oceans.

Although Titan possesses a large subsurface ocean, it also has an abundant supply of a wide range of organic species and surface liquids, which are readily accessible and could harbor more exotic forms of life according to some scientists. Furthermore, Titan may have transient surface liquid water such as impact melt pools and fresh cryovolcanic flows in contact with both solid and liquid surface organics. These environments present unique and important locations for investigating prebiotic chemistry, and potentially, the first steps towards life.

Bodies such as Triton, Pluto, Ceres, Mimas, and Dione are considered to be *candidate* ocean worlds based on hints from limited spacecraft observations. For other bodies, such as some Uranian moons, our knowledge is limited and the presence of an ocean is uncertain but they are deemed *credible possibilities*.

Surface-atmosphere interactions can occur in many ways, including rainfall, surface transport, and evaporation on thick-atmosphere bodies like Titan, condensation and sublimation on thin-atmosphere bodies like Io, Triton, and Pluto, and jet-like and volcanic ejection of materials as on Triton, Io, Enceladus, and perhaps Europa. Atmospheric production of materials through UV photolysis and other processes can also affect the abundance of organics, which eventually reach the surface and perhaps interior, as on Titan and perhaps Pluto and other places. Such interactions are complex and unique on a variety of outer solar system bodies and bear detailed study to fully understand.

Volcanism, the release of material from the interiors of bodies to their surfaces and atmospheres, occurs with unknown frequency and distribution across the solar system. Io is the most volcanically active world in the solar system and a mission to Io is key to understanding the tidal heating that affects ocean worlds. It is of paramount importance to be able to recognize cryovolcanic processes because they reveal past or present endogenic activity and allow us to observe, and perhaps reach exposures of liquid water and potential ocean deposits on the surface. Such processes can substantially modify the geology of icy bodies, by erasing impact craters and reducing the surface age, smoothing out or burying older terrains, and bringing volatiles from the interior to the surface as seen on Io, Enceladus, and possibly Titan, Europa, Ariel, Ganymede, Triton and Pluto. Cryovolcanism also provides a link between interiors and atmospheres, controlling how and how often volatiles are supplied to the atmosphere.

Some of the most important considerations for ocean world habitability are to investigate environments that could provide geochemical disequilibria for extant life, and to understand the past environments of these worlds to determine if the geochemical conditions were ever sufficient to drive an emergence of life. The metabolic strategies that would be utilized in a particular environment would depend on the available geochemical free energy, i.e. the available electron donors and acceptors. Oxidants can be produced by processes such as radiative processing of ice, yielding e.g. O₂, H₂O₂, SO₄²⁻, CO₂; any of these can be used as an electron acceptor for life if it is convected into the ocean at a high enough rate to be in close proximity to electron donors.

In ocean worlds where there is a water-rock interface, electron donors (fuels) could be provided to the oceans by serpentinization reactions, in which water interacts exothermically with Fe-Mg-silicate interior, resulting in high-pH (pH ~ 10–12) vent fluids rich in H₂, CH₄, and a variety of hydrocarbons. Serpentinization and the production of alkaline vents has been theorized for Europa and Enceladus; whether the other common types of hydrothermal vents on Earth, which are mostly produced by plate tectonics, could exist on ocean worlds is unknown. Also important for understanding habitability would be the composition of the oceans – for example the available species of phosphorus, nitrogen, iron and trace metals – and the properties of the rocky seafloor. Triton could be another world where the ocean is in contact with the silicate core, making Triton comparable to Europa and Enceladus in potential for habitability.

What types of minerals would we expect to precipitate on the seafloor of an ocean world and how would they affect the local environment? Carbonate precipitation, for example, is highly dependent on depth/pressure, CO₂ concentration in the ocean, and temperature. Hydrothermal precipitates are significant as well: for example, many vents on Earth build “chimney” structures of metal sulfides, which are electrically conductive and can provide an electron source for life at the seafloor, even abiotically driving redox reactions with surrounding ocean oxidants. Vents, depending on the type, can also precipitate sediments including sulfides/sulfates, clays, iron oxides/hydroxides – and some of these minerals can help catalyze redox reactions and concentrate biologically significant materials. For example, iron hydroxide precipitates (thought to have been common in ocean sediments and hydrothermal precipitates on the early Earth) can sequester and concentrate phosphates and organic molecules, can exert a major control on nutrient cycling by efficiently scavenging trace metals e.g. Ni²⁺ and can drive nitrogen redox chemistry. The concentration of oxidants in the ocean, the delivery of oxidants to the seafloor, and the sedimentation rate, are also significant: life in Earth’s seafloor sediments can respire (albeit at low rates) hundreds of meters below the surface due to penetration of O₂. How deep might oxidants penetrate into seafloor sediments on ocean worlds, and how deep might we have to go to find gradients / life today?

The evolution of ocean worlds over their history is also relevant, in order to determine if they ever had the conditions necessary to facilitate the emergence of life in the first place (as it is possible for a world on which life never emerged, to still be considered “habitable” today). The alkaline hydrothermal origin-of-life model, which describes a prebiotic scenario applicable to the icy moons, posits that serpentinization reactions led to geochemical pH / redox gradients, and these combined with particular iron/nickel minerals that could act as nano-engines, drove metabolism into being from initial electron donors of H₂ and CH₄, and electron acceptors of CO₂ and NO₃²⁻. So, what was the extent of water/rock interaction on ocean worlds: continual throughout their history; episodic; sufficient to maintain pH and redox disequilibria for geological time periods? Did these worlds contain the ingredients necessary for life as we know it – not just CHNOPS but also Mo, Fe, Ni, and the other metals that were likely an integral part of the first electron transfer metabolism? What was the pH of the ocean; was it acidic enough to produce a gradient against an alkaline hydrothermal fluid; and how has that changed over time?

The giant planets (hydrogen-rich Jupiter and Saturn, and water-rich Uranus and Neptune) are responsible for the formation, evolution, and continued existence of their moons’ water-based oceans. Other aspects of these host systems (rings, rocky satellites, and the magnetospheres) help shape the environment of these oceans and play other critical roles such as tidal heating.

Current satellite formation mechanisms dictate that the materials found in ocean worlds – including the water ice “bedrock” materials – are closely associated with the composition of the host world. Understanding the bulk composition of giant planets is thus key to understanding the composition of their satellites. The predominance of trace materials such as hydrocarbons, nitriles, and other materials can, working with liquid water, form key astrobiological precursor material.

Under the warming, tidal influences of their parent planets, ocean-filled moons evolved to their current (possibly habitable) state. For example, Europa’s deep ocean is maintained largely by tidal heating driven by an eccentric orbit around Jupiter, maintained by the resonant orbits of Io and Ganymede. The interior structure of the host giant planet, which influences how well it gravitationally couples to its satellites, as well as the gravitational interplays among all components

of the system, are therefore relevant to understanding the energy balance of ocean-bearing satellites.

More speculatively, high energy particles impacting satellites may also be a factor in the energy available to drive ocean chemistry. Modulated by particles released by satellites including Io and Enceladus, charged by the host giant planet's magnetosphere, these charged particles plus cosmic rays can create disequilibrium species on an ocean world's surface which, if coming into contact with the ocean, open new pathways for pre-biotic (and biotic) chemistry.

7.2 The Search for Life in Ocean Worlds

Ultimately, our astrobiological goal in the outer solar system must be more than to answer the question "Is life present?". We should also answer "Why does life exist where it does, and why not elsewhere?". Our exploration strategy to answer this question should be systematic, with each mission furthering our understanding, as recommended in the "Science Strategy for the Exploration of Europa" chaired by Ron Greeley and John Wood, National Academies Press, 1999. We quote below from the executive summary:

The Need for a Systematic Program of Exploration

COMPLEX recognizes the frustration that will inevitably result from following a well-conceived strategy for conducting a thorough and detailed investigation of the potential for life on Europa that likely will take one or two decades to carry out. With the excitement today about searching for life elsewhere, it is tempting to advocate a spacecraft mission that will immediately search for European life or return samples of surface ice to Earth for such analyses. However, the history of space exploration suggests that a phased approach, in which the results of one mission provide the scientific foundation for the next incremental advance, is more productive in the long term.

We need only look to the history of the search for life on Mars to see the wisdom of an incremental approach. Although the Viking missions seemed very well conceived in 1970, they look naive today in the light of current understanding of the martian environment, and of the diversity of life on Earth and its ability to survive in extreme conditions. As a result, Viking did not sample the most appropriate environments in its search for extant life on Mars. The results from the Viking biology experiments, though, have provided a remarkable foundation for understanding of martian geochemistry that is playing a key role in knowing how and where to look for life on Mars today.

In a similar vein, the absence of identifiable surface environments that might support life or contain evidence of life on Europa and our complete lack of understanding of the chemical environment of the icy surface layer, the liquid water layer that may or may not underlie it, and the rocky interior of Europa suggest that a detailed exploration of the satellite will provide the best opportunity to answer these exciting questions. In other words, understanding the history of the satellite and the potential for life requires a detailed investigation into the geochemistry of the surface and subsurface ice or water, and of possible organic molecules or biological activity. Measurements of the atmosphere, ionosphere, the rocky interior, and the ice- or water-rock interface will also be important.

The search for life in our solar system is intrinsically a search for life on ocean worlds, past or present. This connection between *ecosystems* and *oceans* is recognized by NASA's organization of the Roadmaps to Ocean Worlds (ROW) working group, which has drafted two documents to guide ocean world exploration in the coming decades; ROW Goals and ROW Priorities. This section draws heavily from the text of these two documents. The importance of ocean worlds is

also evident through a series of NASA-sponsored Ocean Worlds meeting held in Washington, D.C. in 2015, at the Woods Hole Oceanographic Institution in 2016, with a third to be held at the Lunar and Planetary Institute in Houston, Texas in 2018. These workshops have been instrumental in coordinating activities between Earth oceanographers and planetary scientists; stronger collaboration between these two groups will hopefully lead to the more efficient development and testing of technology, and ultimately a more informed search for extant life and ecosystems.

The oceans of the outer planets offer numerous challenges and opportunities in the search for extant life. The ROW Goals document outlines a series of research questions that focus on 1) searching for extant life at known habitable ocean worlds, which requires 2) characterizing habitability of known ocean worlds, which in turn necessitates 3) characterizing ocean environments in known ocean worlds, and 4) understanding where/why oceans are present. The considerable effort represented in the ROW documents can be summarized by the following four questions that represent research priorities/goals for the planetary science, life detection, and Earth oceanography communities:

1. What are the target bodies that provide an optimum of sample access and habitability (i.e. the likelihood of supporting an extant ecosystem)?

The ROW Priorities document lists the known ocean worlds by order of (perceived) mission priority. Europa, Titan, and Enceladus are deemed the highest priority by having confirmed oceans and some constraints on habitability. Of these Europa may have the greatest potential for Earth-like life, but may present unique life detection challenges as a result of its location in Jupiter's radiation belt and interactions with Io's ion torus, in addition to an ice shell. Titan's dense atmosphere and surface hydrocarbon lakes provide unique (and potentially lower cost) sampling opportunities, but these environments are at best geologically isolated from any subsurface water ocean. The low temperature and unusual organic composition of Titan's surface makes Earth-like surface life unlikely, challenging conventional life detection methods. Like Europa, Enceladus is covered by an ice shell, but certainly vents material from its liquid interior through plumes. These diffuse plumes provide sampling opportunities, but any recovered material may be of low density, altered by the ejection process, and may be not representative of an interior ecosystem. The provenance of any subsurface-derived material expressed on the surface of these ocean worlds must be understood in terms of chemical and physical processing, in order to evaluate the potential of these materials to preserve biosignatures.

2. What specific attributes of the optimal target body(ies) need to be investigated before sample acquisition and life detection technology can be deployed there?

The success of a life detection mission will depend in large part on what is known about the target body. The more that is known, the better the mission can be planned to exploit unique opportunities or avoid specific challenges. Opportunities include active surface faults or plumes that can provide access to relatively fresh oceanic material, thin spots in otherwise thick ice shells, and subsurface lakes that exist well within the norms of habitability on Earth. Challenges include obstacles on the surface that can damage spacecraft, or surface rheology that can confound efforts to access representative material.

3. What are the sampling and sample processing technologies that are required to facilitate the best life detection technologies when deployed to the optimal target body(ies)?

Plausible arguments have been made that the limiting technological factors to life detection on ocean worlds is not the detection methods themselves, but the sample access and processing steps. With the exception of Titan's organic liquids and the ocean-sourced Enceladus plume, the ocean worlds of the outer planets are covered by ice of varying thickness; this presents a considerable obstacle to collecting representative samples. A variety of methods have been proposed to collect surface ice including coring, rasping, cutting, and direct melting. All of these methods have advantages and disadvantages, but none overcomes the central problem of material alteration during the long transit through the ice shell and radiation processing at the near surface. A variety of ice penetrators have been envisioned that can directly sample a subsurface ocean and communicate findings to a lander, but there are considerable implementation challenges that need to be overcome including cost, power, communication, instrumentation, and mass imposed on the delivery vehicle.

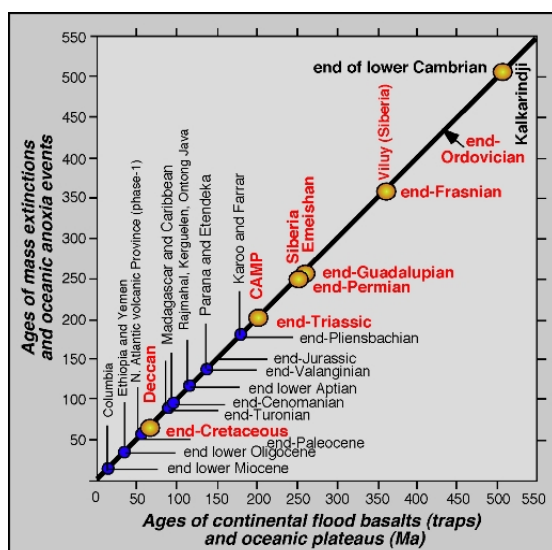
4. What are the (combinations of) technologies that can unambiguously detect an extant ecosystem?

The logistics of accessing representative samples from the ocean worlds listed as high priority is compounded by uncertainty in how best to identify life. The Viking legacy weighs heavily on current and future mission planners, and *unambiguous* life detection strategies are still needed. An ideal positive detection will likely be the result of combining parallel, independently ambiguous positive signals into an unambiguous combined signal. Individual instruments contributing to such a signal may include microscopy (motility and morphology), mass spectrometry (compound detection, chirality and isotopic quantification), spectroscopy (compound detection), imaging (biofabrics, biominerals), and fluorescent tagging and/or lab-on-a-chip (compound-specific detection, chirality quantification). Given the challenge of identifying individual cells and quantifying cellular activity in Earth's oceans, the maturity of life detection technology should not be overestimated.

8.0 OPAG RELEVANCE TO WORLDS NOT IN THE OUTER SOLAR SYSTEM

Comparative planetology is key to understanding the workings of planetary systems (V&V Q10). Here we wish to emphasize that exploration of the outer solar system can uniquely foster understanding of fundamental processes affecting terrestrial planets and exoplanets, as well as other outer planets and moons. We note that V&V did not list any outer planet missions as supporting Q3: “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?” We wish to highlight here, based largely on new results not considered in V&V, three examples where proposed outer planet missions (to Io, Titan and Ice Giants) do contribute significantly to Q3.

1. Very high effusion rate volcanism has played a major role in the evolution of terrestrial planet surfaces and atmospheres. At least four of the five Phanerozoic mass extinctions on Earth were precisely correlated in time with pulses in flood volcanism. Io is the only place in our planetary system where we can directly observe such high effusion rates.
2. The early atmospheres of Earth and even of Mars are thought to have been highly reduced, containing abundant methane. Understanding such atmospheres is key to understanding the early evolution of life on Earth and perhaps Mars. There is only one world in our star system with a thick methane-rich atmosphere: Titan. A future mission to better understand Titan’s atmosphere would be a major step towards understanding the early habitability of terrestrial planets and exoplanets.
3. Migration of the ice giants early in our solar system’s history may be responsible for the late heavy bombardment in the inner solar system, thought to have provided many of the volatiles (such as water) found on the terrestrial planets today. This is key to understanding the composition of the terrestrial planets and the emergence and subsequent evolution of life. Noble gas abundances (e.g. neon and argon) and isotopic ratios (e.g. $^{14}\text{N}/^{15}\text{N}$) can be tracers of the formation temperature—and hence location of formation—of giant planets in the early solar system.

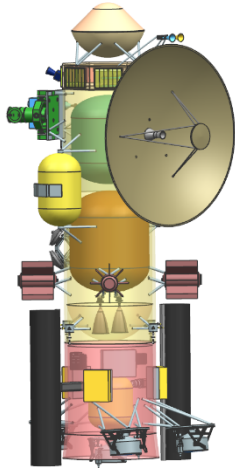


Phanerozoic mass extinctions happened during very high effusion rate pulses in volcanism.

9.0 TECHNOLOGY

Given the scientific goals discussed in the previous sections, missions needed to fulfill those goals will require technological advances in many areas. Some will be engineering advances but some missions will require the use of new technologies. We specifically exclude discussion of the solar-powered Flagship mission in development, Europa Clipper, other than to point out that many radiation-hardened components and sub-systems for instruments and the spacecraft have been developed and can be used in future missions.

9.1 Ice Giants



*Proposed Neptune Orbiter
with Probe, SEP; 50 kg P/L
7364 kg wet*

The Ice Giant Planet(s) mission envisaged as the next Flagship mission by the Decadal Survey is limited by power, mass and data rate. It requires a long-lived, efficient *radioisotope power system*. The Enhanced Multi-Mission Radioisotope Thermoelectric Generator (eMMRTG), which is expected to have higher available power at end of life than the MMRTG currently in use, is being developed, and is enabling for missions to Uranus and Neptune. The Ice Giants study (2017) http://www.lpi.usra.edu/icegiants/mission_study/Full-Report.pdf called for the need to complete the development of both the eMMRTG and the thermal protection system, Heat-shield for Extreme Entry Environment (HEEET). Both HEEET and Phenolic-Impregnated Carbon Ablator (PICA) are also being developed for use on the Giant Planet probes and should continue to be funded. Advanced radioisotope systems would also be welcome to ensure higher power availability for longer missions but so far these next generation power systems are only in the study phase. Power and mass are extremely limiting for the science instruments, so the *continued* development of miniaturized, low mass/power instruments is vital for these missions and existing miniaturized instruments need to be matured.

Electric Propulsion (EP) enables missions requiring large in-space velocity changes over time and can often provide enhanced and enabling trajectories to the outer planets. This technology opens up mass and trip-time trades, offering major performance gains and significant improvements to mission capabilities. Solar Electric Propulsion (SEP) would enable a flagship orbiter to Neptune in 12-13 years if implemented as separable stage to minimize propellant required for insertion. Development efforts are underway for NEXT, but flight verification is still required and could be achieved if CAESAR (Comet Astrobiology Exploration Sample Return) is selected in the New Frontiers competition.

Although not discussed in the Ice Giants study, *Communication* advances, such as the use of Ka-band and a large deployable lightweight antenna could enable a 10-fold increase in data rate from Uranus or Neptune, thus enabling instruments to take data continuously or, if the mass was reduced, to increase the number of instruments. Pointing requirements and mass will dictate the optimal size of the antenna but given the vast distance from the sun the stable orbiting environment will allow accurate calibration of the attitude control system. More capable transponders as well as technologies to increase the radio frequency (RF) power-aperture product, i.e., RF power amplifier output power times the area of the antenna aperture, are key to increased data return—as well as improved tracking and radio science. Ultimately, the move up to optical frequencies

will also bring improvement but over a much longer time frame. Such technological improvements, of course, will also help other missions, for example Titan and Enceladus orbiters and KBO missions.

Aerocapture is a technology to reduce the required propellant mass carried by a spacecraft. The technology has been available for over a decade, but it has not been used for a variety of reasons. When combined with aerocapture, SLS would enable reduced flight times for both Uranus (< 5 years) and Neptune (< 7 years). Efforts to limit travel time typically increase a spacecraft's arrival velocity, increasing the ΔV required for orbit insertion. For orbit insertions requiring a large ΔV , aerocapture offers advantages over chemical propulsive orbit insertions by reducing the mass of propellant required. This allows greater science payload mass, shorter trip times, and/or reduced total mass at launch. In the 2017 Ice Giants study, Aerocapture was not chosen but future studies might yet require it particularly if *advances in navigation* can establish that a traditional low L/D body vehicle could be used. High-L/D vehicles would be an expensive new technology development, so it would be advantageous if we could reduce the entry flight path angle (EFPA) uncertainties to the point that heritage aeroshell shapes have theoretical corridor widths larger than those uncertainties. Devising ways to improve that planet-relative navigation and reduce the EFPA uncertainties is done by research into *Astrodynamics* - the application of celestial mechanics to the design of spacecraft trajectories and to the navigation of spacecraft. Funding in Astrodynamics, even at a low level, would significantly improve our ability to design more efficient and novel missions.

9.2 Ocean Worlds

Key to accomplishing the goals of exploring Ocean Worlds are technology advances that satisfy the environmental constraints of extremely low temperatures and often high radiation while meeting the stringent planetary protection requirements of Ocean Worlds, which itself requires novel methodologies be employed. For a full discussion of the Technologies required for Ocean Worlds, see the ROW report on Priorities, Mission Strategies and Technologies.

There are many common mission technologies to Ocean Worlds missions. *Communications* and the need to have communication elements that have reduced mass, power and volume to efficiently transmit high data rates from/to landed elements. The above discussion for the Ice Giants missions applies also to Ocean World missions. *Power sources and energy storage systems* suitable for cryogenic environments and autonomous systems are required for all missions envisaged. Since these missions will be far from Earth, *autonomous systems and subsystems* are key to enabling the aerial or landed functionalities and scientific measurements. To facilitate autonomy, we must continue to fund *improvements in computer capabilities*. Most Ocean World missions will have a requirement for *cold-compatible, low-mass, low-power instruments, mechanism and electronics* with the possible exception of those housed in radiation-hard containers, which double as warm enclosures. For landers and plumes, the *sample acquisition and handling mechanisms* are at ambient, as are many of the instrument components. Additive manufacturing of complex and multi-purpose structures will enable mass savings without compromising performance.

Even the communication advances needed for the Ice Giants missions will not fully support Ocean Worlds missions. These highly complex missions in which planets rotate (taking landers out of view), orbiters get occulted by the bodies they are orbiting, science operations divert resources

from communication, relay communications are indispensable, etc. will benefit from Disruption (or Delay) Tolerant Network development that is currently operational on the ISS. In these circumstances, uninterrupted continuous end-to-end communication can never be assured; manually commanding spacecraft communication activity is labor-intensive and expensive under the best of conditions, and in an environment as dynamic as this one, over extremely long signal propagation latencies, it will not be efficient. DTN enables automated flight mission communications by deploying a network, similar to the Internet, to reduce costs and scale-up operations. The Internet itself will not work for this, because the Internet protocols rely on brief round-trip communication exchanges; they cannot function over interplanetary distances and frequent connectivity lapses (between tracking passes). Delay-tolerant networking protocols solve the problem. They are:

- Robust: network automatically recovers from data loss and station hardware failure.
- Secure: cryptographic measures for data integrity and/or confidentiality.
- Capable: priority-driven transmission, file transfer, video streaming.
- Interoperable: internationally standardized.
- Mature: multiple implementations, and ISS is using DTN today.

The technology is proven for Earth missions and the ISS and now needs to be incorporated into planetary science missions.

Planetary Protection technologies are continually evolving as we respond as our increased understanding of the Ocean World bodies. Planetary Protection requirements for Ocean Worlds are very different from Mars and probabilistic approaches are being considered along with potentially new methodologies. Technology advancements in microbiology and molecular biology in the last decade can now be utilized to provide enhanced genetic resolution on what specific biological contamination is present on the spacecraft and semi-quantitatively determine how much is present. This emerging molecular biology based method is called Metagenomics. It provides an in-depth, comprehensive analysis of viable organisms on the spacecraft leading to a tailored, more efficient and cost effective microbial reduction plan for each hardware item on a spacecraft. In addition, utilizing this approach increases the resolution on the actual risk of microbial contamination for the targeted extraterrestrial bodies. The development of Metagenomic technologies from the current research-based environmental applications to a mainstream spacecraft application would be a leap forward in technology advancement for the planetary protection discipline and benefit all future missions by appreciable increases in spacecraft functionality, reliability, and mission success.

Many *in situ* technologies for Ocean Worlds can be grouped into those needed for bodies that have a thick atmosphere (Titan) and those that do not, those that are within the radiation field of Jupiter and those that are not. However, the technologies developed for the Jupiter system bodies can be used in less demanding radiation environments but not *vice versa*. In most cases (again excluding Titan with its thick, complex organic atmosphere and crust), and depending on the gravity of the body, the lander technologies are similar for surface characterizations, *in situ life detection and sampling methods e.g. subsurface ice acquisition/handling and plume capture, planetary protection technologies and ice sample return with cryogenic preservation*. Titan is very different in that a landed bio-signature detection strategy would be one of looking for a small amount of complex replicating molecules in thick deposits of a widely varying solid organics or in a

hydrocarbon lake, while on most of the other bodies it may well be looking for small amounts of organics in an otherwise poorly characterized icy environment.

There are many types of instruments that can fulfill the measurement goals of Ocean Worlds, but all benefit from having low mass, power and volume. In general, the instruments also need to have high resolution and high sensitivity because the molecules/cells of interest are low in concentration, cover a small region of space or are simply spatially minute. The instruments that focus on Habitability and Life Detection are described in the ROW *Priorities, Mission Strategies and Technologies* report, which defers to the community to continue development of chemical sensors, spectrometers, seismometers, cameras *etc.* that could aid in the goals outlined in the Goals, Objectives and Investigations for Ocean Worlds document. The higher priority capabilities needed are:

- Identification of regions of concentrated potential biological material from orbit or flyby is needed to determine the most promising regions for further exploration by landers or rovers.
- Sample extraction from plumes and cryogenic ices, particularly if the sampling must be done at km depths.
- Sample processing, which is dependent both on the matrix being analyzed and the characterization technique being used.
- Spacecraft instruments that can characterize polymers – particularly polymers of arbitrary structure.
- Detection of microorganisms that are very sparsely distributed in a matrix
- Detection of chemical processes indicative of life such as information transfer, highly specific catalysis, and micro-environments in which the chemistry is tightly controlled. Although alien molecules that perform these functions may differ from terrestrial, it is likely that they will carry out these functions.

Depending on the architecture of each mission, technologies for survival and operation of both electronic and mechanical systems in cryogenic environments need to be developed and implemented. Some of these are being developed for a potential Europa Lander and such improvements will provide a foundation for maturing these technologies for all Ocean Worlds. Specifically, efforts are underway to develop sample acquisition and handling techniques for cryogenic surfaces as well as compact motor controllers with actuators that can function at the low temperatures of Ocean Worlds. Batteries, intolerant of high and extremely low temperatures are being developed and tested to operate at lower temperatures and withstand planetary protection techniques other than dry heat microbial reduction. These high specific energy per unit mass (Wh/kg) batteries are designed to reduce the mass by ~40 kg and last ~20 days and preliminary tests to achieve planetary protection requirements with gamma ray radiation are proving encouraging. Funding should be continued for these technologies whether or not the Europa Lander becomes a mission, since they will benefit multiple missions.

Also under study for a Europa Lander is precision de-orbit, descent and landing (DDL). Continued funding of all these technologies are critical. Terrain relative navigation has been developed for Mars and is applicable to airless Ocean World bodies. This same approach to precision landing is applicable to airless Ocean Worlds with modest evolutionary changes, because airless bodies allow similar orbital reconnaissance at relatively high resolution. The surfaces of some Ocean Worlds, particularly Europa, are thought to be rough enough that onboard landing hazard detection during

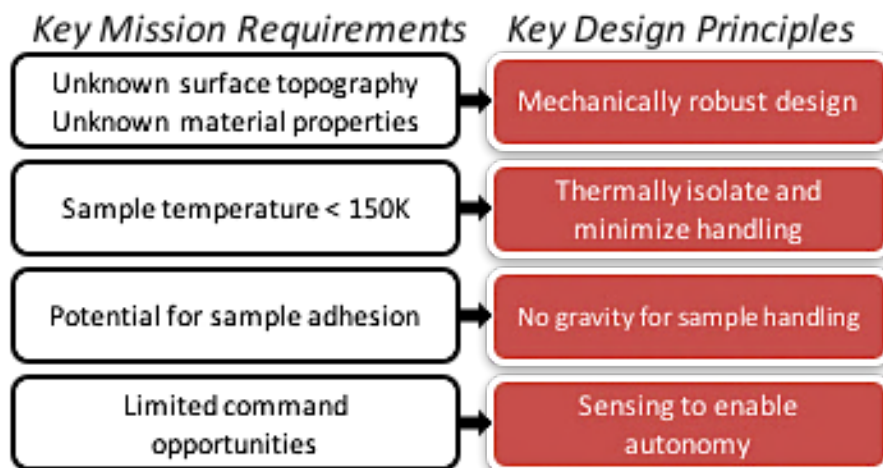
descent is essential. The Europa lander study team has already begun to address these needs, which will lay the groundwork for application to other airless bodies. A digital map of a candidate safe landing site will be developed which feeds into the Intelligent Landing System (ILS) on the Europa Lander that comprises algorithms and a sensor suite with a:

- Terrain-Relative Navigation (TRN) camera to determine map-relative position and velocity and
- Laser Imaging, Detection and Ranging (LIDAR) sensor to map hazardous features below map resolution and provide altimetry to enable pinpoint landing on Europa and detect and avoid landing hazards. The TRN camera must determine position <50m and touchdown velocity <0.1 m/s with 1200 krad TID and the LIDAR must generate 100m x 100m map with 5 cm ground sampling from 430m at 0.5 Hz with 1200 krad TID.

More compact and power efficient landing radars, which have been utilized successfully landing on Mars for many years, should also be in mix of landing systems to be developed. Depending on the surface conditions and/or landing scenario, radar may be an attractive stand-alone sensor or compliment to TRN and LIDAR.

Titan is a different case, because its thick, high, hazy atmosphere limits orbital imaging of the surface to spatial resolutions that are orders of magnitude lower than is possible for Mars and airless bodies. For orbital imaging from Cassini, resolutions are 100s of meters to a few kilometers per pixel, versus tens of centimeters for Mars; for future Titan orbital missions, the resolution currently contemplated is still only 10s of meters per pixel, and there is no guarantee that such a mission will take place before a lander that could benefit from the higher resolution orbital reconnaissance. Moreover, the hazy atmosphere highly absorbs and scatters visible and near infrared light, so wavelengths that provide the best surface imaging from orbit are infrared and radar. Descent cameras use visible to near infrared wavelengths, so onboard position estimation with descent images requires radically different methods than current precision landing systems. Therefore, precision landing on Titan needs a technology development that is distinct from other Ocean Worlds.

Europa lander studies are addressing sampling depths up to 0.2 m with the following as key mission requirements and design principles.



Beyond that, considering science objectives and potential technical solutions, three classes of penetration depth goals have been defined:

- Class 1: depths of 0.2 to 10 m
- Class 2: depths of 10 m to ~ 1 km
- Class 3: depths greater than 1 km, all the way down to the liquid water ocean.

Major hurdles to overcome are to develop system-level ice penetration and sampling capability to operate in extreme cold (~@100K), stay within plausible mass, power, and volume constraints (order of magnitude 100kg, 100W) of landed missions while meeting COSPAR requirements that the probability of forward-contamination of the ocean be less than 10^{-4} per mission. This requires technology advances in

- Low-power, low-mass excavation,
- Sample handling and transport, and
- Sterilization as needed to prevent forward-contamination.

All of the penetration and sampling should be capable of autonomous operation since the round trip light time to most of the Ocean Worlds of interest is significant. Representative testbeds and simulators are critical in ensuring the success of these developments.

Although portions of the Ocean Worlds missions can be achieved using sequenced-based spacecraft, operations could be substantially reduced with a move to an autonomous vehicles. With the onset of cultural acceptance of autonomy in our daily lives, and the availability of increasing computation power, the time has arrived to transition our space missions from sequenced, ground-in-the-loop machines to self-driving space vehicles. Considerable work needs to be done in the area of demonstrating Autonomy for planetary missions, and this will have to be demonstrated to be routine before outer planet missions can consider them, but in the long run this will prove invaluable.

There are many types of instruments that can fulfill the measurement goals of Ocean Worlds, but all benefit from having low mass, power and volume. In general, the instruments also need to have high resolution and high sensitivity because the molecules/cells of interest are low in concentration, cover a small region of space or are simply spatially minute. This section covers those instruments that could focus on Habitability and Life Detection, and defers to the community to continue development of chemical sensors, spectrometers, seismometers, cameras *etc.* that could aid in the goals outlined in the Goals, Objectives and Investigations for Ocean Worlds document. The higher priority capabilities needed are:

- Identification of regions of concentrated potential biological material from orbit or flyby is needed to determine the most promising regions for further exploration by landers or rovers.
- Sample extraction from plumes and cryogenic ices, particularly if the sampling must be done at km depths.
- Sample processing, which is dependent both on the matrix being analyzed and the characterization technique being used.
- Spacecraft instruments that can characterize polymers – particularly polymers of arbitrary structure.
- Detection of microorganisms that are very sparsely distributed in a matrix
- Detection of chemical processes indicative of life such as information transfer, highly specific catalysis, and micro-environments in which the chemistry is tightly controlled. Although alien

molecules that perform these functions may differ from terrestrial, it is likely that they will carry out these functions.

No mission has returned *actively* cooled samples to Earth. The Stardust and Genesis missions returned *passively* cooled samples to Earth, but allowed samples to reach 50°C (323K) during atmospheric entry. Returning ice samples from an Ocean World, such as from the plumes of Europa, requires a carefully thought out systems approach ensuring the sample acquisition methodology functions flawlessly with an Integrated Cryogenic Chamber and a Back Planetary Protection system – all designed to operate together.

Technologies for miniature systems – CubeSats and SmallSats – can potentially be useful for exploring the outer planet systems, most likely as ‘daughter-craft’. Some of the newer SmallSat technologies will one day be able to reduce the mass of orbiting and landed missions in a similar fashion. NASA is continuing to fund concepts and with the SIMPLEX call novel ideas can be expected to progress. OPAG recommends continued investment in miniaturization and low mass/power concepts as this will benefit all outer planetary missions.

The technologies discussed need to have *stable, on-going funding* if outer planetary exploration is to continue. For Ice Giants missions the technology investment should begin as soon as possible in order to optimize the trade space and reduce overall mission costs. With the onset of an Ocean Worlds program, NASA’s Planetary Science Division now has a Technology Office, PESTO, that can focus on the technologies required for these planetary bodies. The community has input into the need and direction required for the technologies and provided inputs into roadmaps, so the only limitation now is funding. In order to make substantial gains in understanding habitability and the possibility of finding life on Ocean Worlds, we recommend that NASA invest in the technologies described in this document.

10. TELESCOPIC OBSERVATIONS

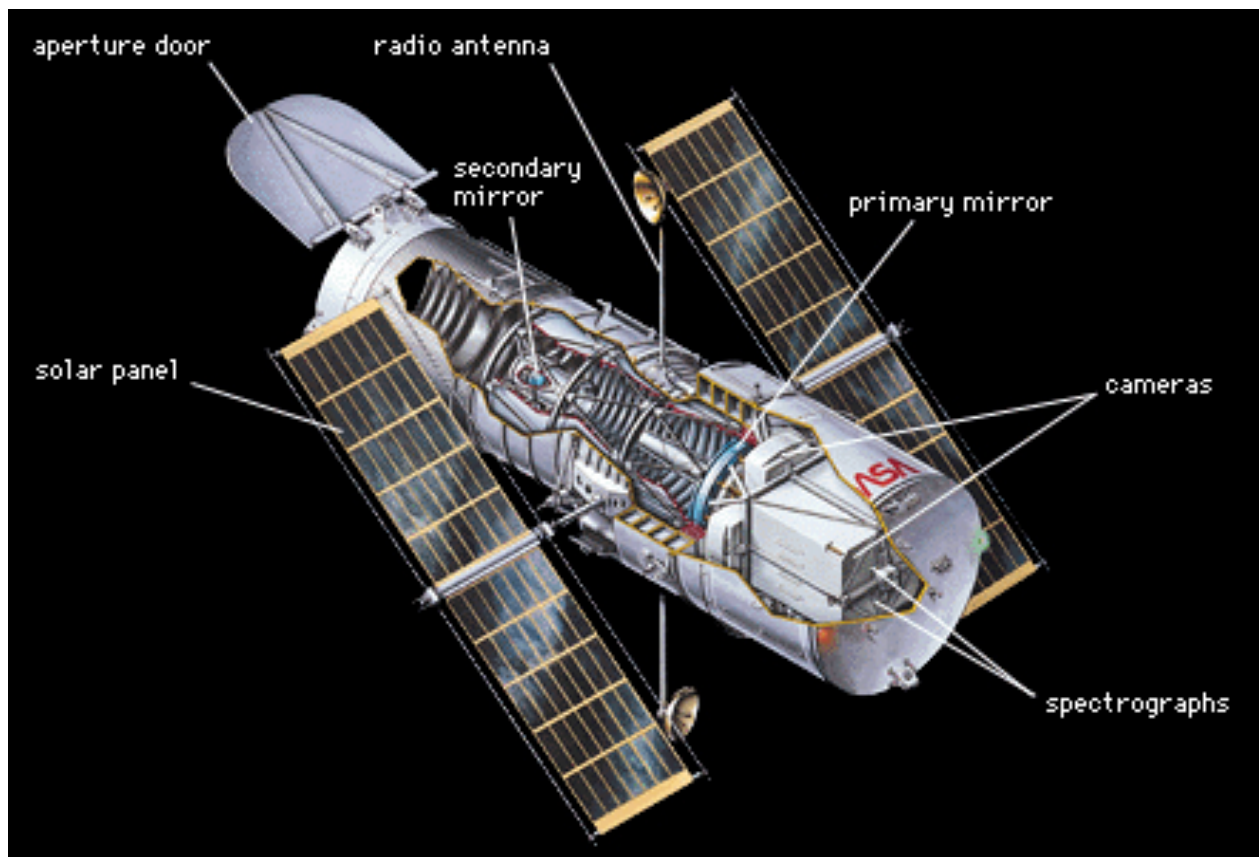
Earth-based telescopes, both ground-based and space-based, are vital for supporting outer planets science. Data from Earth-based telescopic studies are beneficial monitoring dynamics of systems and are critical in preparations for spacecraft missions to targets. Earth-based observations allow us to study temporal variability in giant planet atmospheres, Titan's atmosphere, rings, and Io's volcanism on time scales not possible from an in-situ spacecraft and at significantly lower cost (albeit with lower spatial resolution). They also enable comparative surveys, using the same instrument to observe many objects (e.g. spectral properties of KBO planets).

Ground-based observations will be critical in the coming years for addressing some of the questions outlined in this OPAG Goals document, including:

- Identifying storms in the atmospheres of Jupiter, Saturn, Uranus, and Neptune, tracking their meridional and longitudinal motions, and determining their lifetimes.
- How and when do changes in Titan's atmosphere occur, and how are these expressed at the surface? What processes occur in Titan's atmosphere and on the surface that lead to the formation of organic molecules, and could these materials undergo prebiotic and biotic processes? Recent IRTF observations are looking for hydrocarbons and complex molecules in Titan's atmosphere.
- What are Europa's surface, ocean, and interior compositions? Ground-based observations can be used to determine surface composition through infrared spectroscopy.
- What are the magnitude, spatial distribution, temporal variability, and dissipation mechanisms of tidal heating within Io? Because there are few spacecraft in the outer solar system, Earth-based observations are the only way to fill gaps in monitoring temporal variability in Io's volcanic output. How do the density and composition of Io's atmosphere vary temporally and spatially, what controls the variability, and how is the atmosphere affected by changes in volcanic activity?
- How do material and energy flow within and between the Io torus and Jupiter's magnetosphere and how does that change with time? Is Io's magnetospherically-driven volatile loss an archetype for similar volatile loss processes that may have been important elsewhere in the solar system and beyond? How does Io's atmosphere affect the state of the Io torus, the Jovian magnetosphere, and aurorae? Near simultaneous observations of Io's volcanoes and the Io plasma torus will tell us how Io's volcanoes affect changes in the torus and other magnetospheric phenomena. This can best be accomplished with a combination of ground-based and space-based observations. For example, JAXA's Sprint-A mission in earth orbit is regularly observing Io's magnetosphere.
- In recent years, Hubble observations have been critical in igniting the interest in search-for-life opportunities at Europa, after detection of (apparent) plume activity.

HST studies have been important in studies of auroral activity on Saturn (in coordination with Cassini) using the unique UV capabilities of HST. HST was also used to successfully find target choices for New Horizons following the Pluto encounter (New Horizons is now on course for one of them, 2014 MU69). Hubble observations remain a high priority for outer planet research, particularly because there is no ultraviolet-optical high-resolution alternative from the ground.

OPAG is concerned about the impending loss of the unique capabilities of HST and urges NASA to highlight space-based telescopes for planetary science in the next Discovery AOs, as recommended by the Visions and Voyages Decadal Survey. OPAG favors the CAPS recommendation for a mission study in advance of the next Decadal Survey on a Dedicated Telescope for Solar System Science that would conduct detailed studies of dynamical processes on numerous solar system objects that are now precluded by demands for observing time in large telescopes and at wavelengths inaccessible from the ground.



Hubble Space Telescope

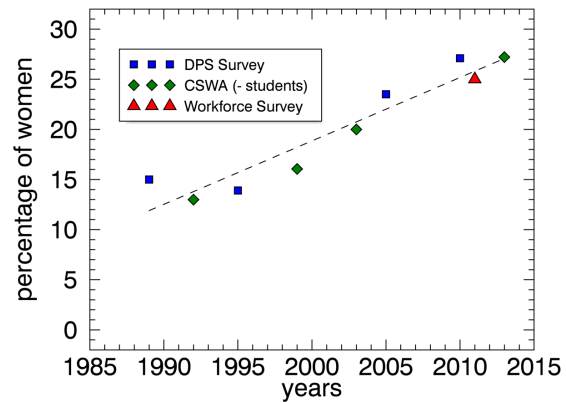
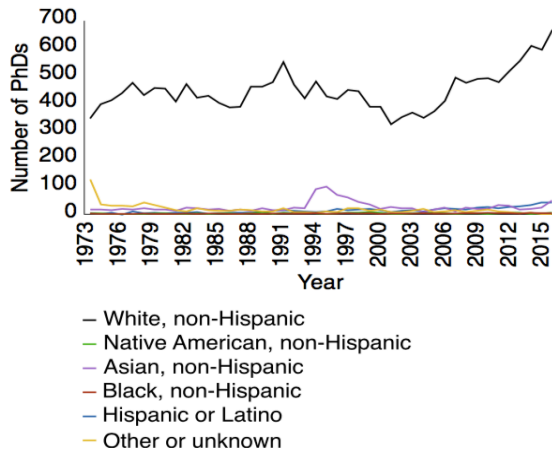
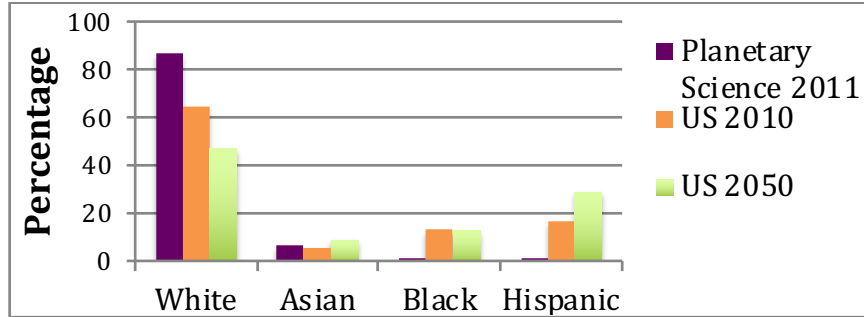
11. WORKFORCE ISSUES

The planetary science workforce is not nearly as diverse as the society from which its membership is drawn and from which the majority of our funding comes. Relative to the general population, the current planetary science workforce has an underrepresentation of African American, Indigenous, and Latinx members, as well as an underrepresentation of women from all backgrounds. While the percentage of women in planetary science has increased from ~15% in the late-1990s to >25% by the early 2010s, once they are in the field, women still lag behind in some measures of success, including involvement in spacecraft mission science teams. The number of women on these teams has remained stagnant at 15% for the past 15 years. Recent studies have shown that women, particularly women of color, frequently face systemic challenges that prevent them from entering and/or succeeding in planetary science. In addition, while there have been no specific studies concerning the participation of members of racial and ethnic minority groups in planetary science over time and/or career stage, the number of earned geoscience doctorates by members of these groups has not increased in the past 40 years. The low numbers of racial and ethnic minorities on spacecraft mission teams may be a direct result of this.

Groups with diverse memberships are able to find more innovative, creative, and responsive solutions to complex problems. In recognizing this, NASA has included the following statement in last New Frontiers AO and the 2017 and 2018 ROSES AO: “NASA recognizes and supports the benefits of having diverse and inclusive scientific, engineering, and technology communities and fully expects that such values will be reflected in the composition of all proposal teams as well as peer review panels (science, engineering, and technology), science definition teams, and mission and instrument teams.” We strongly advocate for and endorse steps that increase diversity among scientists who are supported by NASA, including directed projects and PI-led efforts.

Diversity of mission teams is a problem for outer solar system missions in particular, as several decades usually pass between the time that teams are chosen and mission completion. It is therefore necessary that we have plans in place for scientists from more diverse backgrounds, and junior scientists, to contribute early in mission development. This will ensure that these scientists are capable of assuming more responsibilities as missions progress, especially as senior mission team members retire.

In addition, as the racial diversity of the US increases, outer solar system mission teams will look increasingly less like the US population. Thus, in order to inspire future generations of outer solar system scientists, as well as preserve the general population’s interest in scientific exploration, it is necessary that outer planet missions be particularly careful in the composition of their teams, and be specifically mindful of obtaining diversity across multiple axes.



- We recommend that the next planetary decadal survey include an analysis of workforce issues in planetary science, and that the findings and recommendations be documented in the final report. The analysis should include the current demographics of the planetary science community and an overview of social science work on barriers to underrepresented groups in STEM fields (e.g., geology, physics, chemistry) from which the planetary science workforce is drawn.

Female scientists at a Europa Clipper meeting:



12. SUMMARY RECOMMENDATIONS

We recommend future missions in 4 cost categories, as well as technology development, telescopic observations, and ground-based research to support the key science.

For **large directed 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. This re-affirms the importance given to such a mission in V&V. We note that no new technology efforts (aside from finishing efforts already underway) are needed for this mission to proceed. The recent Ice Giants SDT study noted that preferential launch windows for Uranus missions are in the 2030–2034 timeframe with a corresponding window of 2029–2030 for Neptune. Significant funding for Europa Clipper began in 2013 for a 2022 launch; if an Ice Giants mission requires a similar schedule then funding for a Neptune mission should begin in 2020-21.

Our next large directed mission priority is a mission to search for life or biosignatures on an ocean world, most likely Europa or Enceladus. We believe that life detection technology development could prove essential to either mission, so we strongly support the ongoing technology development efforts. The decadal mid-term review recommended that Europa Lander be considered for a new start in the next full decadal survey, rather than beginning sooner. However, a Europa Lander preproject is already funded and could get a new start. If a Europa Lander mission is approved, then OPAG will certainly support that mission. We recommend that NASA study an Enceladus life-search mission. Concurrently, we strongly recommend that the next Decadal Survey include a Priority Question about actual life or biosignature 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. OPAG strongly recommends that the next Decadal Survey be less restrictive in the number of allowed destinations for New Frontiers missions. The rationale for this restriction was not made clear in V&V. The outer solar system has a great abundance of interesting worlds to explore, so such restrictions are particularly concerning to the OPAG community.

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. As in V&V, we do not prioritize potential missions, in the spirit of the Discovery Program.

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.

For mission studies in advance of the next decadal, our recommendations follow OPAG mission priorities. A new, more focused Ice Giants study may be needed, joint with the European Space Agency (ESA), and addressing concerns over the prior study expressed in the Decadal mid-term review. We consider an Enceladus life-detection mission study to be a high priority, perhaps as part of the Saturn systems missions recommended by CAPS. A new Io mission study is needed, because the Io Observer study in V&V was very rushed. The next steps in the study of KBO planets needs to be considered following Pluto systems results from New Horizons, including a potential Pluto Orbiter. A dedicated space telescope for solar system science is needed and would benefit from a study. These recommendations are consistent with those made by CAPS in 2017 and/or the 2018 Decadal mid-term review.

Summary of OPAG Recommendations

Europa Clipper	Continue development towards arrival in 2020s.	
New large-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.
Mission studies for next Decadal Survey	Focused Ice Giants mission study, Enceladus life-detection mission	Io mission, KBO missions, Saturn system missions, dedicated space telescope
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	
Workforce Issues	Next planetary decadal survey should analyze these issues	

Key References

OPAG website: <https://www.lpi.usra.edu/opag/>

Decadal Survey: [PDF][Vision and Voyages for Planetary Science in the Decade 2013-2022](#)

Decadal mid-term review: http://sites.nationalacademies.org/ssb/currentprojects/ssb_177619

NASA Strategic Plan:

https://www.nasa.gov/sites/default/files/atoms/files/nasa_2018_strategic_plan.pdf

The NASA 2016 Ice Giant Study Executive Summary and Full Report:

https://www.lpi.usra.edu/icegiants/mission_study/

[PDF]Europa Lander Science Definition Team Report

Roadmaps to Ocean Worlds (ROW) study reports: <https://www.lpi.usra.edu/opag/ROW/>

New Frontiers NAS Study: <https://www.nap.edu/catalog/12175/opening-new-frontiers-in-space-choices-for-the-next-new>

A Science Strategy for the Exploration of Europa: <https://www.nap.edu/read/9451/chapter/1>

Workforce study: <https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2017JE005256>

CAPS mission study recommendations: <https://www.nap.edu/catalog/24843/report-series-committee-on-astrobiology-and-planetary-science-getting-ready>

2018 NASA Authorization Act: <https://www.congress.gov/bill/115th-congress/house-bill/5503>

OPAG Steering Committee

Alfred McEwen
University of Arizona, Tucson (Chair)

Jeffrey Moore
NASA Ames (incoming Chair)

Linda Spilker
Jet Propulsion Laboratory, (Deputy Chair)

Jason Barnes*
University of Idaho

Pat Beauchamp*
Jet Propulsion Laboratory

Jeff Bowman
Scripps Institute of Oceanography

Morgan Cable
Jet Propulsion Laboratory

Scott Edgington
Jet Propulsion Lab

Amanda Hendrix
Planetary Science Institute

Mark Hofstadter
Jet Propulsion Lab

Terry Hurford
Goddard Space Flight Center

Kathleen Mandt
Applied Physics Laboratory

Carol Paty
Georgia Institute of Technology

Lynnae Quick
CEPS, Smithsonian Institution

Abigail Rymer
Applied Physics Laboratory

Julie Rathbun*
Planetary Science Institute

Kunio Sayanagi
Hampton University

Britney Schmidt
Georgia Institute of Technology

Thomas Spilker
Consultant

Elizabeth Turtle*
APL, John Hopkins University

*Rolling off steering committee after
September 2018 OPAG meeting