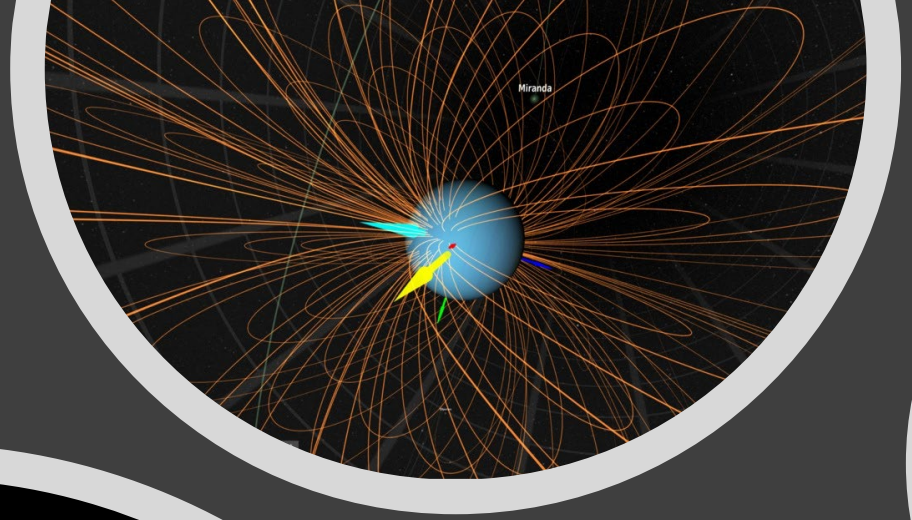
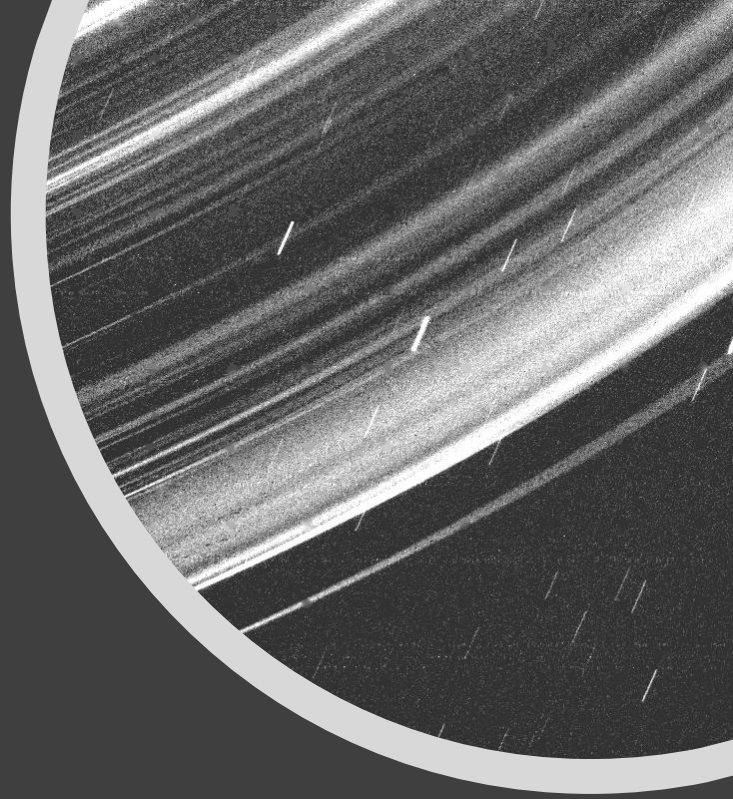
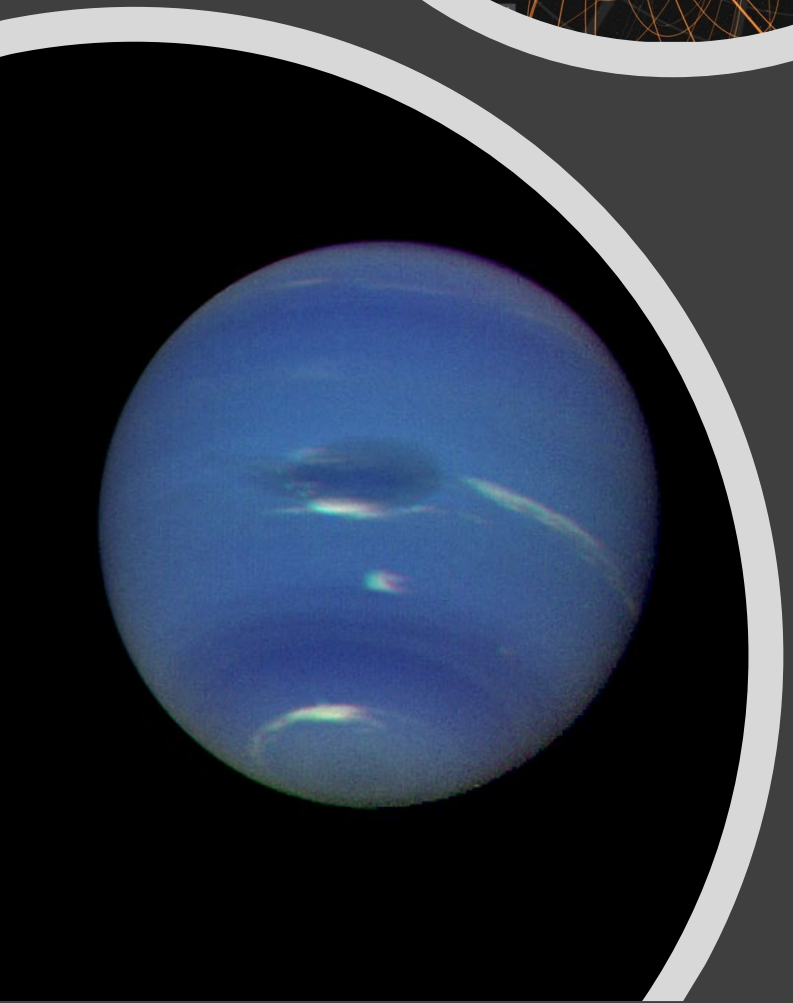






Ice Giant Systems

Amy Simon, GSFC (Chair)
Chloe Beddingfield, ARC/SETI
Adam Masters, Imperial College
Paul Schenk, LPI
Mark Showalter, SETI

w/ input from Jonathan Fortney, UCSC

August 2019 OPAG Meeting

Boulder, CO

Key Outer Planet Unifying Science Themes.

All are addressed by an Ice Giant mission.

Proposed Key Unifying Science Theme #1: **How do planetary systems form?**

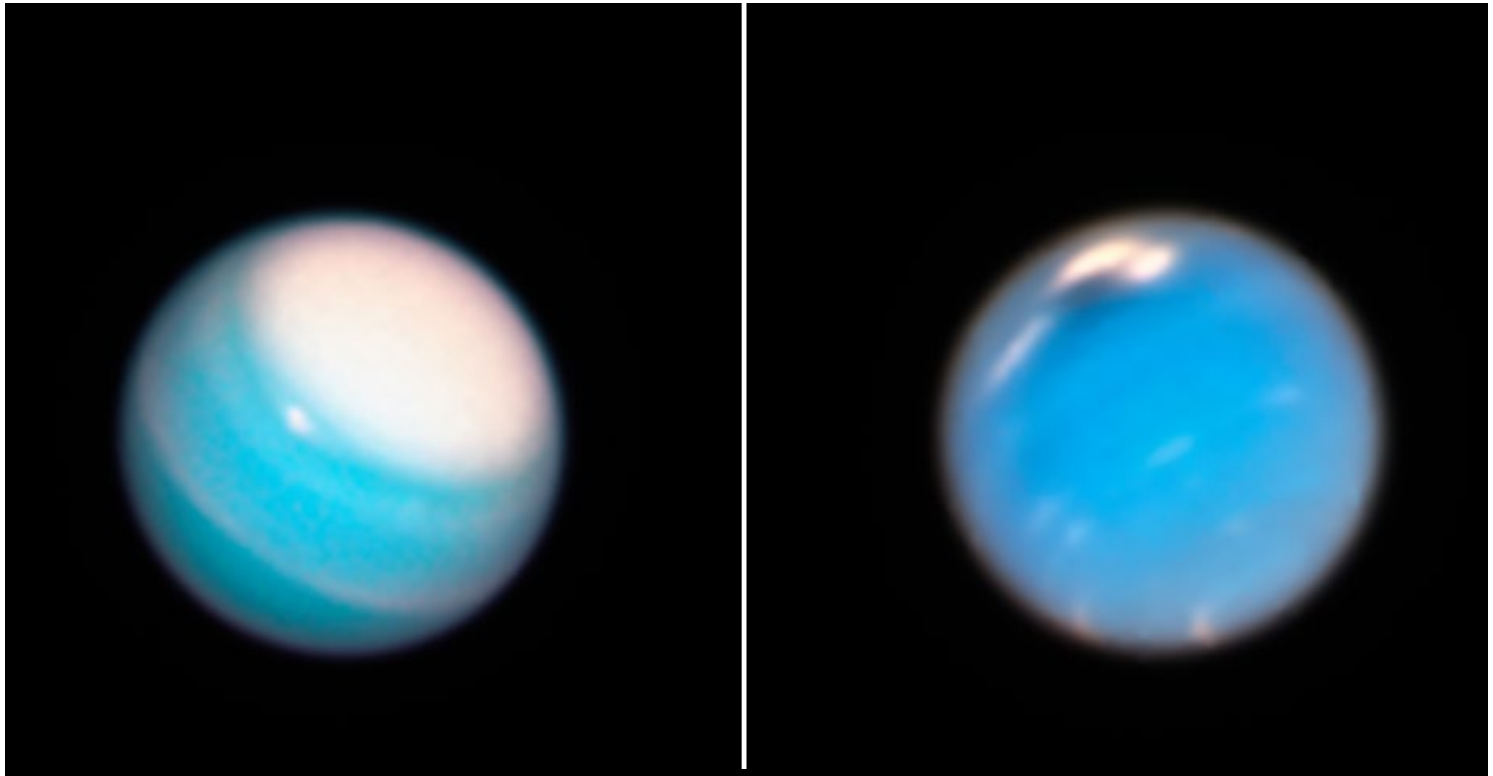
- OPAG disciplines: All
- Non-OPAG disciplines: exoplanets (Astrophysics), Earth Science, small bodies (SBAG), terrestrial planets (VEXAG, MEPAG), the Moon (LEAG)

Proposed Key Unifying Science Theme #2: **Do Life or Habitable Conditions Exist Beyond the Earth?**

- OPAG disciplines: Satellites, Ocean Worlds
- Non-OPAG disciplines: small bodies (SBAG), exoplanets (Astrophysics)

Proposed Key Unifying Science Theme #3: **What Processes Control the Evolution and Current Conditions of Planets?**

- OPAG disciplines: All
- Non-OPAG disciplines: all planetary disciplines plus exoplanets (Astrophysics), solar-magnetosphere interactions (Heliophysics), and Earth Science



Engages every planetary science discipline

Why the Ice Giants?

- Identified as high priority in the last Decadal and remain just as important
- Investigates the last unexplored class of large bodies in the solar system
  - Different class of planet than Jupiter and Saturn
  - Pivotal to understanding solar system formation and evolution
- Each has a unique ring and satellite system
  - Potential for new Ocean Worlds
  - Captured KBOs vs *in situ* formation
- Both have magnetospheric geometries not seen elsewhere
- Most known exoplanets fall in the ice giant size range

Theme 1: How do planetary systems form?

Example* Priority Science Questions

1.1: When and where did the ice giants form, and did they migrate? What is the bulk composition of the ice giant planets? What is the interior structure of the ice giant planets?

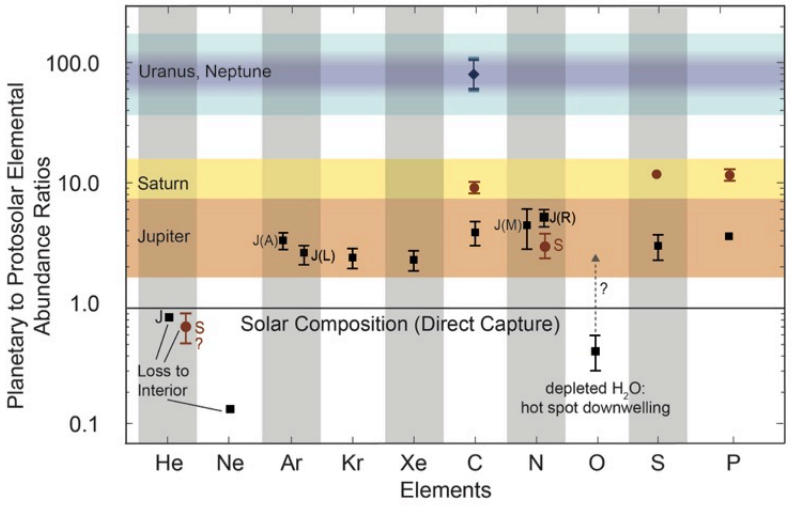
1.2: When and where did the major satellites accrete? What is the bulk composition of the satellites? What is the interior structure of the satellites? Is there evidence of seasonal migration of ices or plume activity?

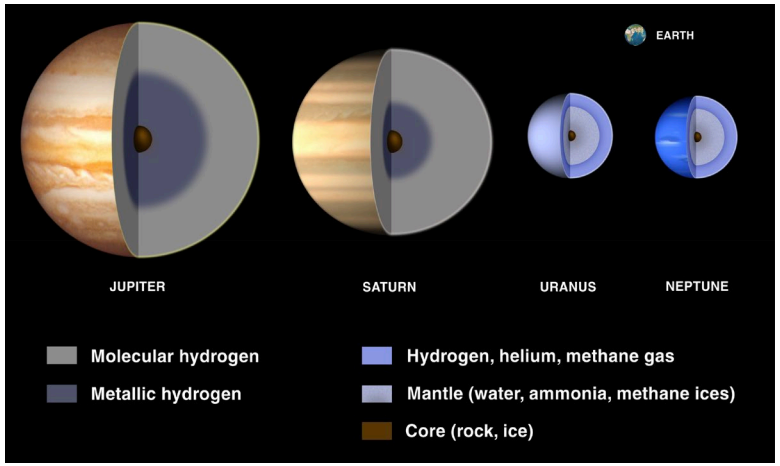
1.3: What was the role of the ice giants in controlling the delivery of impactors and volatiles to the inner solar system?

1.4: What processes active today in the Ice Giant ring and inner satellite systems are relevant to proto-planetary disks?

* There are many more questions, these are a selected subset of the broad science enabled

Atreya et al. 2018

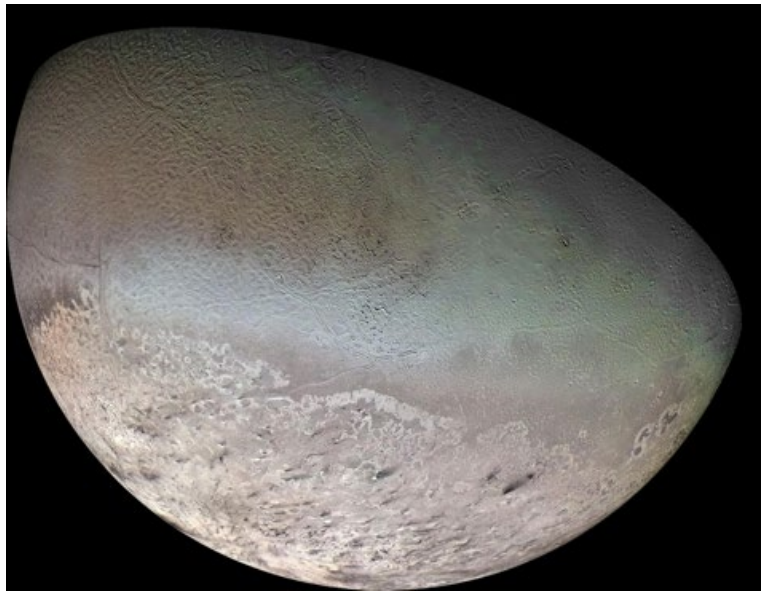




Priority Science Question/Investigation #1.1

When and where did the ice giants form, and did they migrate? What is the bulk composition of the ice giant planets? What is the interior structure of the ice giant planets?

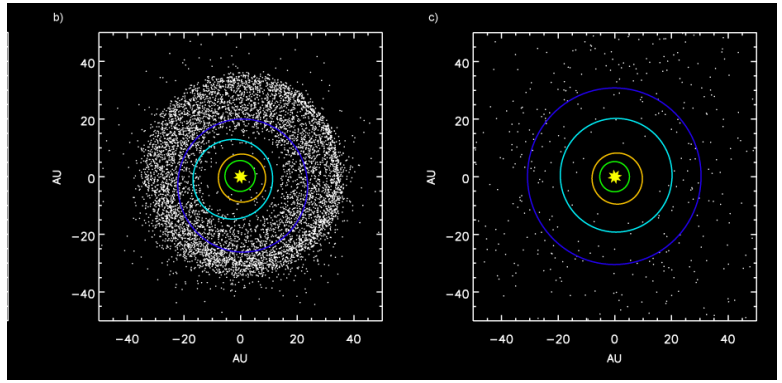
- **Missions:** orbiters, atmospheric probes
- **Possible Measurements:** gravity and magnetic fields, atmospheric (weather layer) cloud structure (remote and *in situ*), elemental, noble gas and isotopic abundances, vertical temperature, wind, and composition profiles, thermal balance
- **Other:** Solar system formation modeling



Priority Science Question/Investigation #1.2

When and where did the major satellites accrete? What is the bulk composition of the satellites? What is the interior structure of the satellites? Is there evidence of seasonal migration of ices or plume activity?

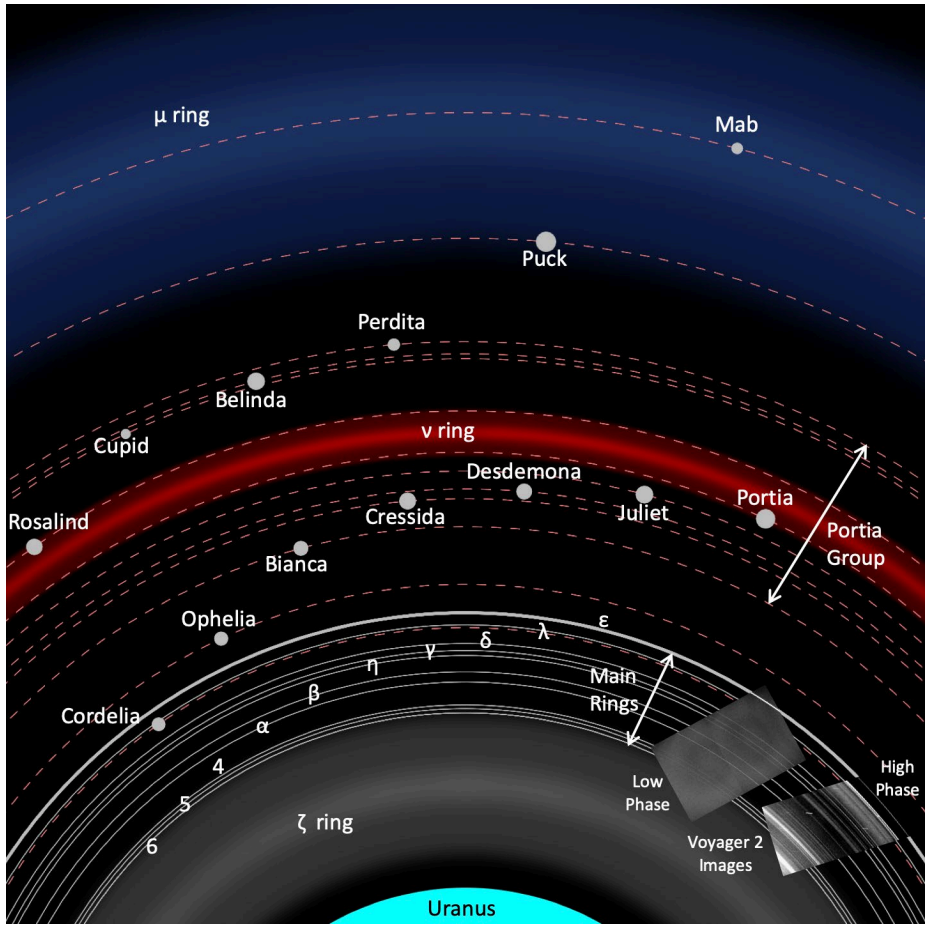
- **Missions:** orbiters, landers
- **Possible Measurements:** composition, geology/surface structure/topography, thermal maps, gravity, magnetic field and plasma measurements



Priority Science Question/Investigation #1.3

What was the role of the ice giants in controlling the delivery of impactors and volatiles to the inner solar system?

- **Missions:** orbiters, atmospheric probe
- **Possible Measurements:** atmospheric (noble gas) composition, thermal balance, composition of small moons
- **Other:** solar system formation modeling



Priority Science Question/Investigation #1.4

What processes active today in the Ice Giant ring and inner satellite systems are relevant to proto-planetary disks?

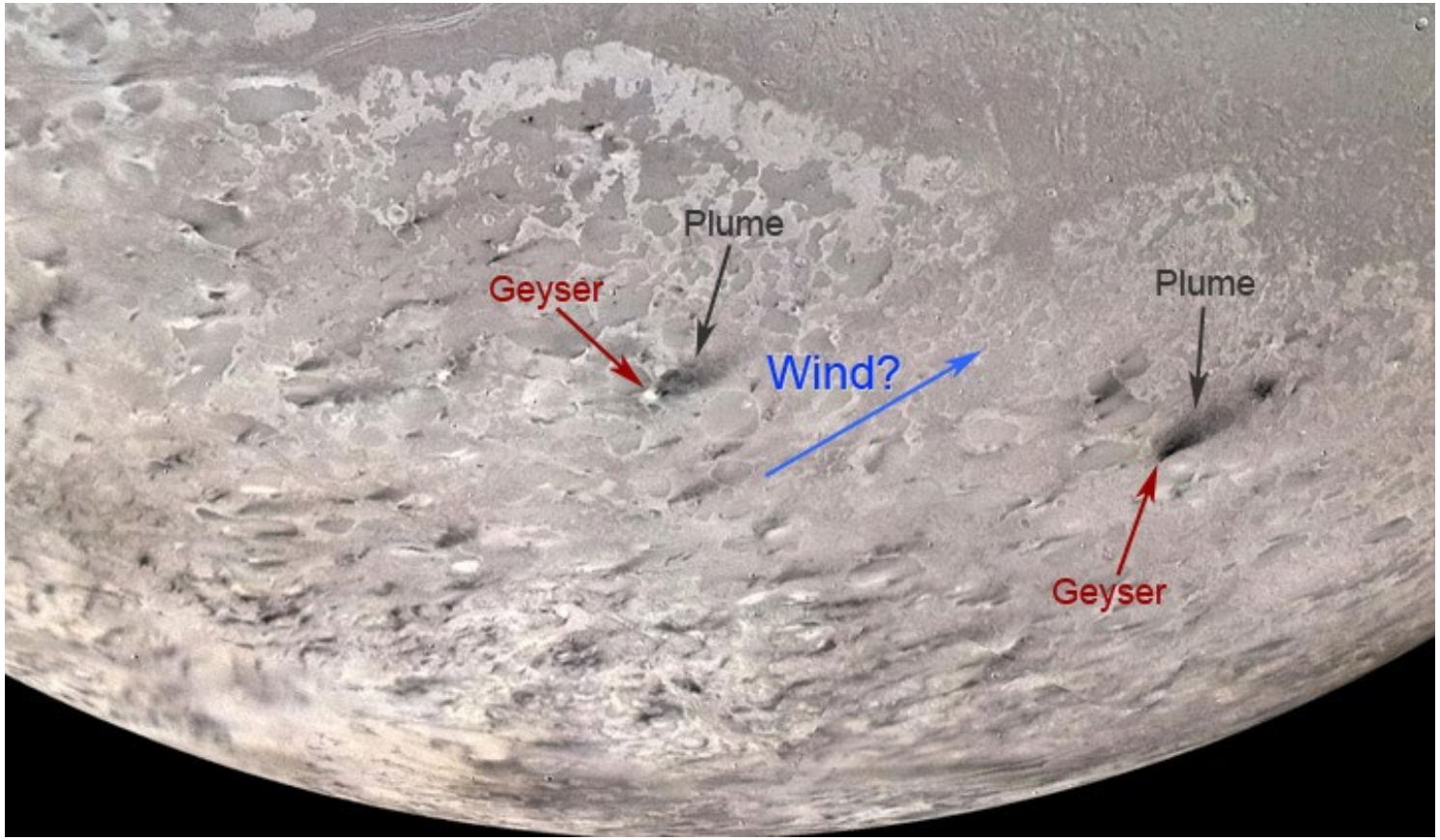
- **Mission:** orbiters
- **Possible Measurements:** ring imaging and spectrometry, precision astrometry, stellar occultations
- **Other:** solar system formation modeling

Theme #2: Do Life or Habitable Conditions Exist Beyond the Earth?

Example* Priority Science Questions:

2.1: Are any Ice Giant satellites Ocean Worlds? Is there evidence for cryovolcanism or plume activity now or in the past?

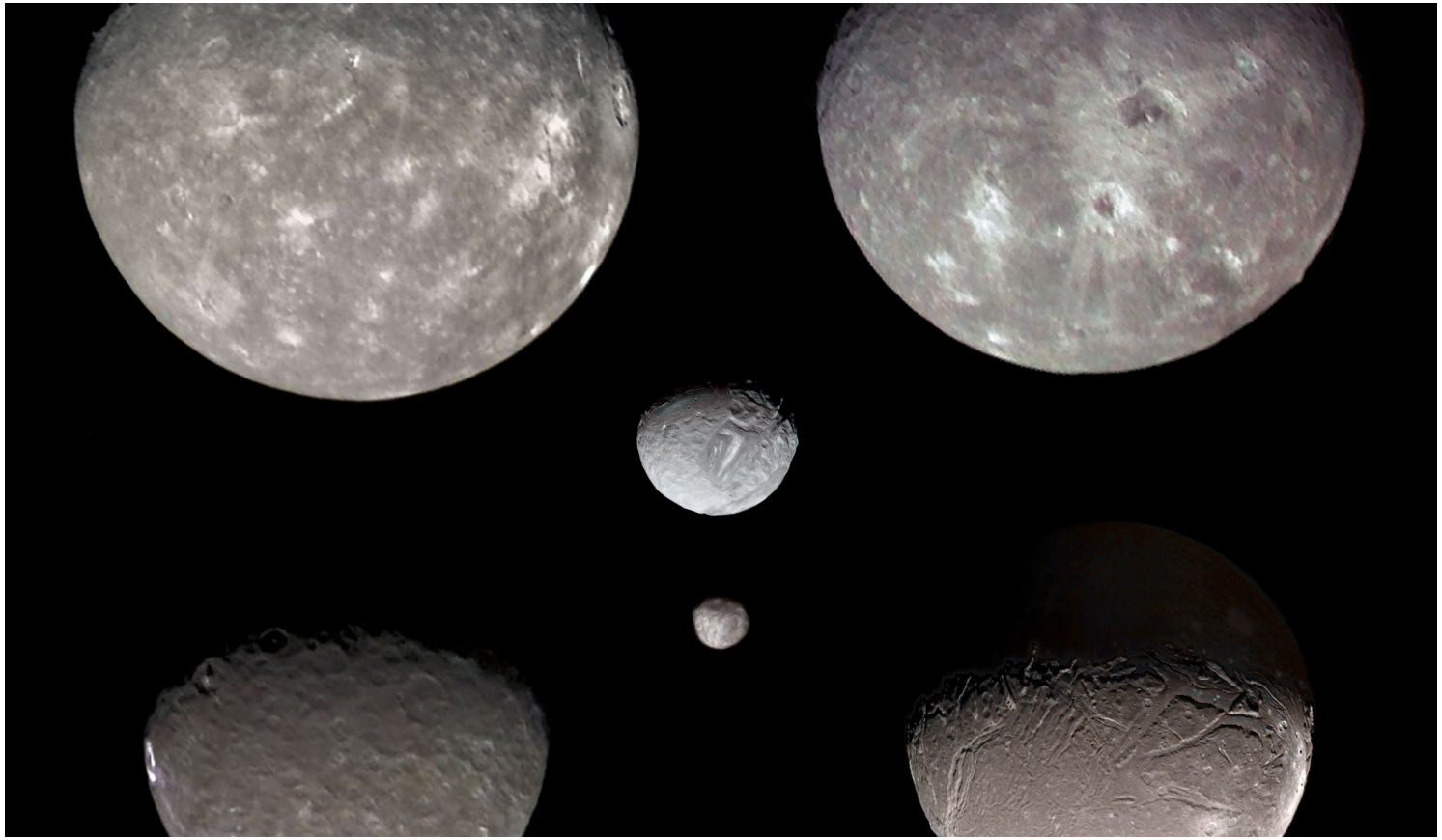
2.2: Are current conditions at any Ice Giant satellite conducive to the existence of life today? Do any Ice Giant satellites currently harbor life? What is the inventory and source of organic matter on the Ice Giant satellites?



Priority Science Question/Investigation #2.1

Are any Ice Giant satellites Ocean Worlds? Is there evidence for cryovolcanism or plume activity now or in the past?

- **Missions:** orbiters
- **Possible Measurements:** composition, geology/surface structure/topography, thermal maps, gravity, magnetic field and plasma measurements



Priority Science Question/Investigation #2.2

Are current conditions at any Ice Giant satellite conducive to the existence of life today? Do any Ice Giant satellites currently harbor life? What is the inventory and source of organic matter on the Ice Giant satellites?

- **Missions:** orbiters
- **Possible Measurements:** composition, geology/surface structure/topography, thermal maps, gravity, magnetic field and plasma measurements

Theme #3: What Processes Control the Evolution and Current Conditions of Planets?

Example* Priority Science Questions:

3.1: How do the Ice Giant magnetospheres and atmospheres respond to the impulsive solar wind forcing created by their unusual geometries? What affect does solar insolation play on weather and upper atmospheric structure?

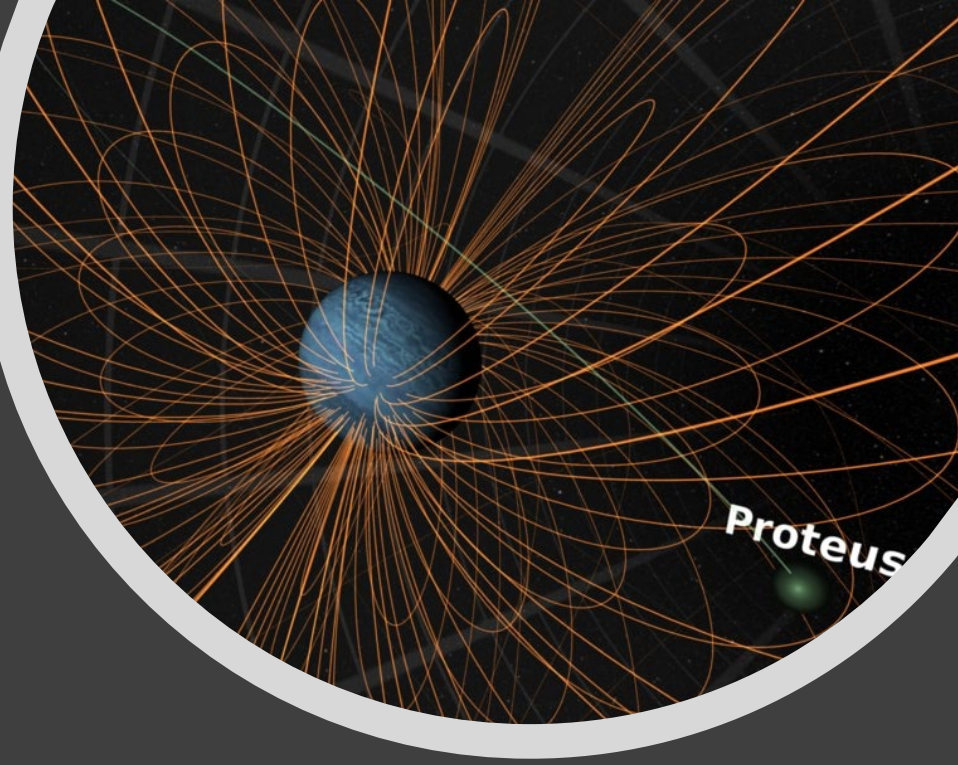
3.2: How does the interior structure vary between Uranus and Neptune (and that of the gas giants)? Why does Uranus appear to release an order of magnitude less internal energy than does Neptune? How does convection work on ice giants and how does it influence weather and winds?

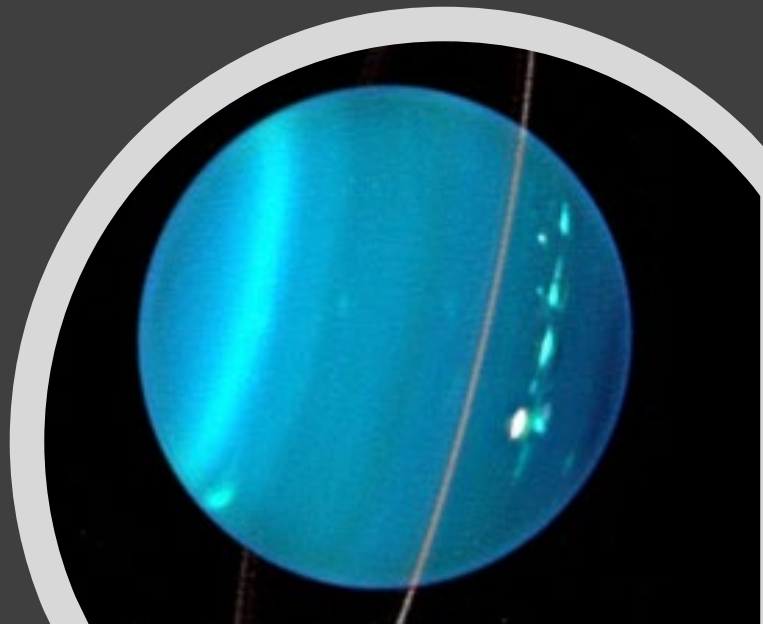
3.3: What is the nature of the interactions between Ice Giant rings and satellites? Do any of the satellites show current geologic activity? How do the satellite/rings systems vary between Uranus (formed *in situ*) and Neptune (captured and disrupted)

Priority Science Question/Investigation #3.1

How do the Ice Giant magnetospheres and atmospheres respond to the impulsive solar wind forcing created by their unusual geometries? What affect does solar insolation play on weather and upper atmospheric structure?

- **Missions:** orbiters, atmospheric probes
- **Possible Measurements:** magnetic field structure, charged particles, structure and dynamics of the ionosphere and thermosphere, atmospheric (weather layer) cloud structure, vertical thermal and composition profiles

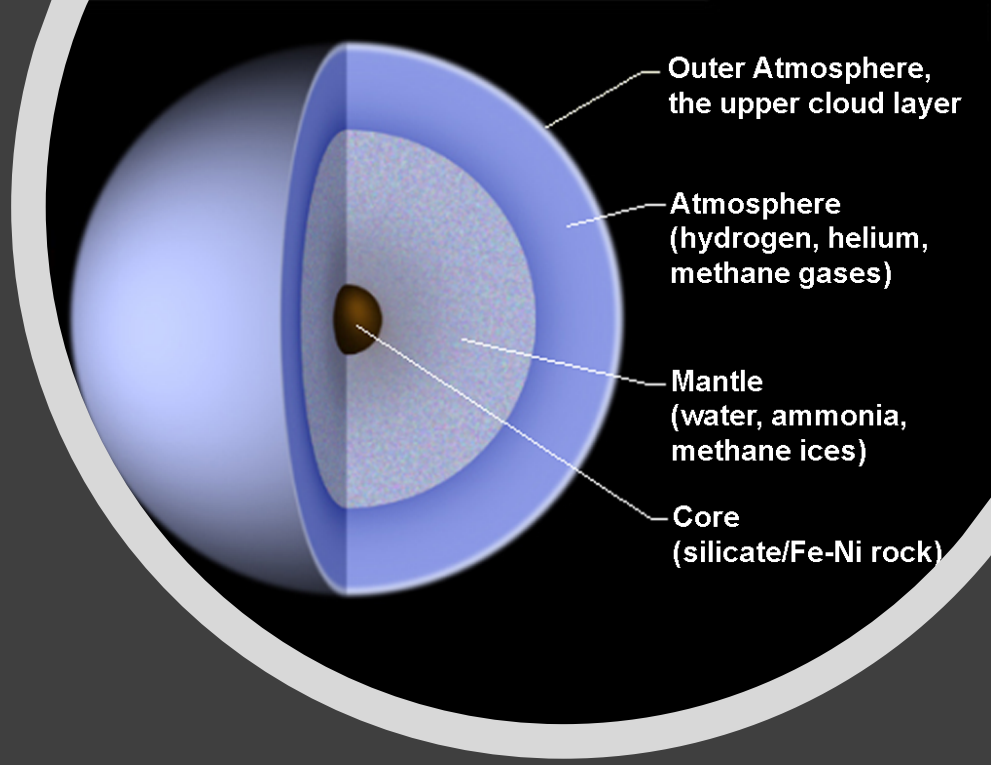


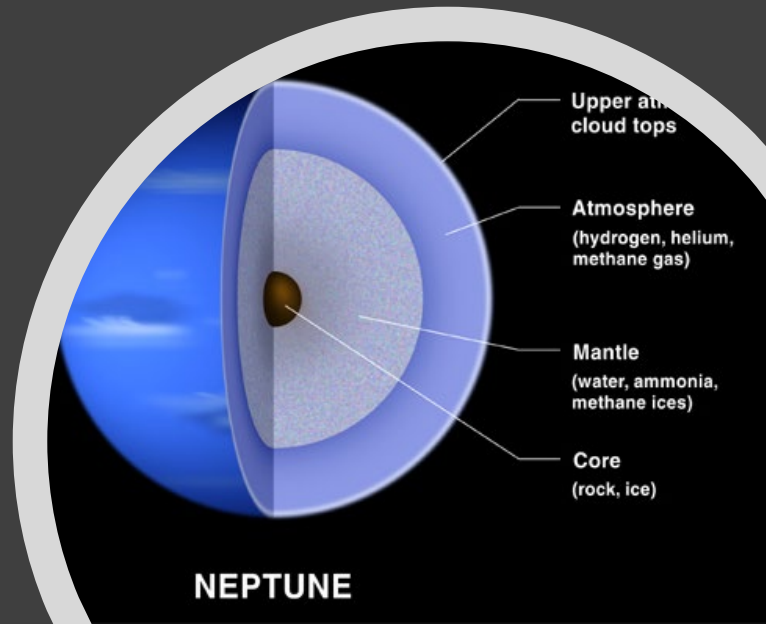


Priority Science Question/Investigation #3.2

How does the interior structure vary between Uranus and Neptune (and that of the gas giants)? Why does Uranus appear to release an order of magnitude less internal energy than does Neptune? How does convection work on ice giants and how does it influence weather and winds?

- **Missions**: orbiters, atmospheric probes
- **Possible Measurements:** thermal balance, composition (remote and in situ), atmospheric (weather layer) cloud structure (remote and in situ), vertical wind and temperature profiles, gravity and magnetic field measurements, elemental, noble gas, and isotopic abundances.

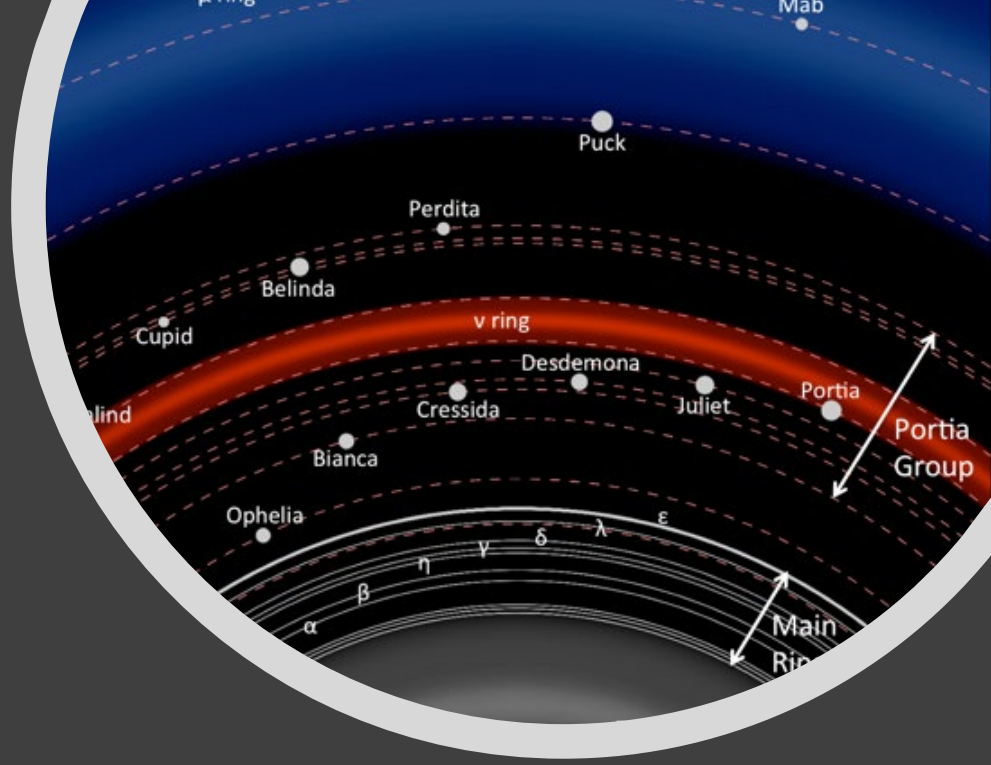


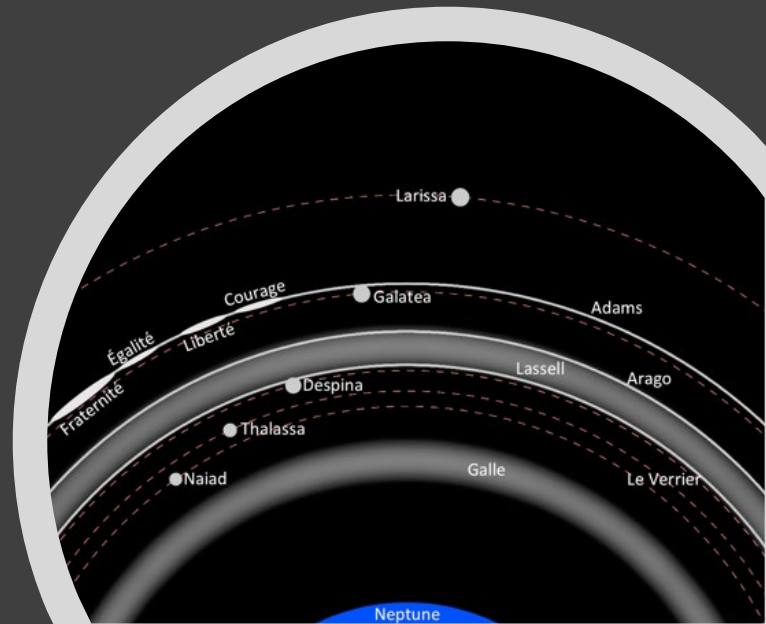


Priority Science Question/Investigation #3.3

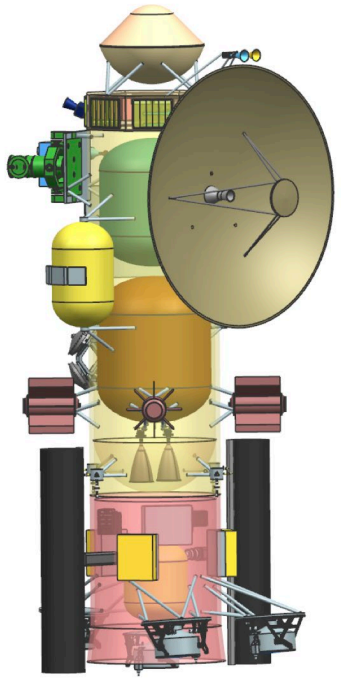
What is the nature of the interactions between Ice Giant rings and satellites? Do any of the satellites show current geologic activity? How do the satellite/rings systems vary between Uranus (formed *in situ*) and Neptune (captured and disrupted)

- **Missions:** orbiters
- **Possible Measurements:** composition, geology/surface structure/topography, long-term tracking of orbital dynamics, precision astrometry, stellar occultations

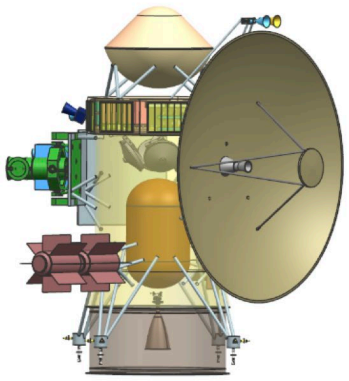




Ice Giant System Missions



Neptune Orbiter with Probe, SEP, and 50 kg payload, launch mass = 7364 kg



Uranus Flyby with Probe 50 kg payload, launch mass = 1525 kg

- A long-lived orbiter is required to explore all aspects of an Ice Giant system, particularly the satellites, rings, and magnetosphere.
  - Crucial atmospheric measurements require an entry probe.
- While Uranus and Neptune are equally compelling, they are not equivalent. Each planet has something to teach us the other cannot.
- A Flagship mission to either of the Ice Giants will achieve compelling science across a broad range of disciplines, including planetary science, exoplanets, and space physics.
- Opportunities to explore both Ice Giants should be considered.
  - Recent NASA and ESA studies have explored dual-launch missions to both
  - Community white paper about a joint Neptune Flagship and NF Uranus mission that also meets dwarf planet/KBO/Centaur objectives

Ice Giant Systems Panel Summary

Most top priority questions posed in the Vision and Voyages Decadal Survey are addressed by exploration of an Ice Giant System

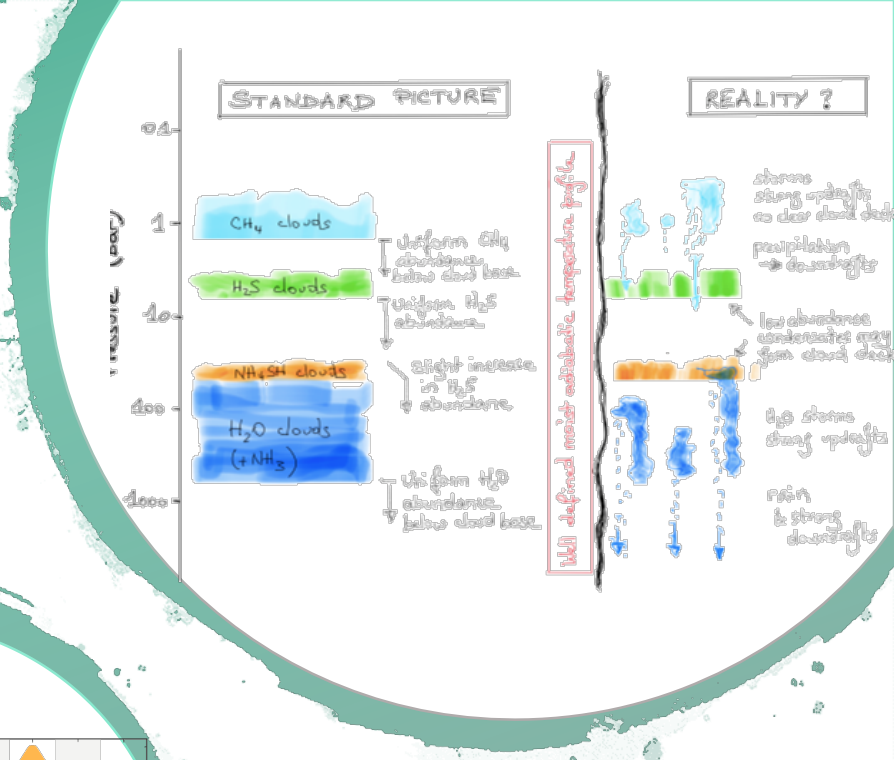
- An Ice Giant Flagship was recommended for flight after Mars 2020 and Europa Clipper
- Those same goals and objectives still apply to an Ice Giant mission
- The least explored class of planets, and the most unexplained

Exploration of an Ice Giant System engages all planetary science disciplines, and is crucial to understanding the majority of known exoplanets

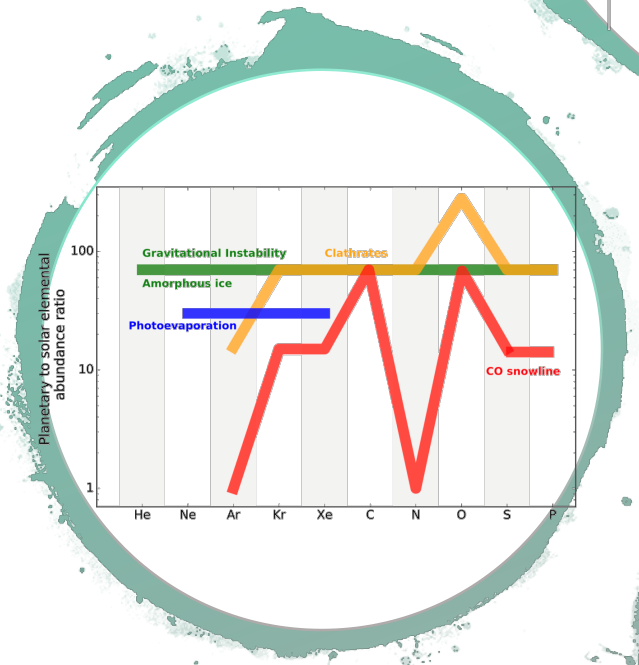
- A long-lived Ice Giant orbiter with atmospheric probe is required
- Uranus and Neptune are each a compelling and unique destination
- Joint missions that reach both within practical cost and risk profiles are desirable

High impact atmosphere and interior science

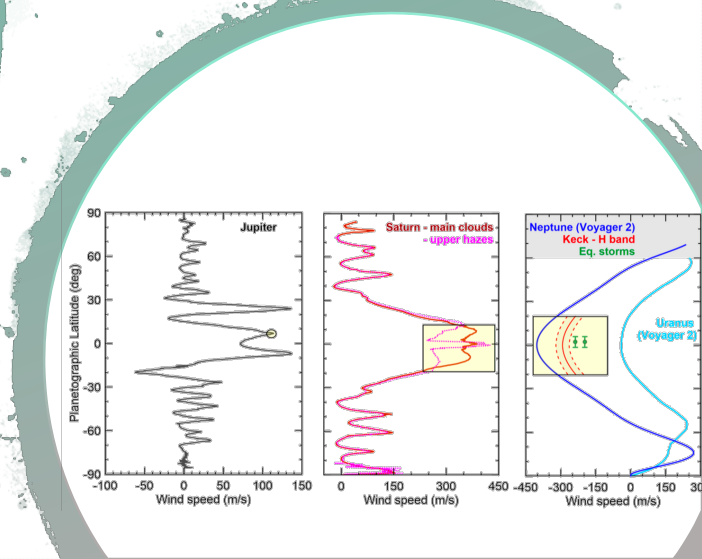
- Uranus and Neptune have a much higher percentage of ices than Jupiter and Saturn, but noble gases tell the detailed formation history
- Large differences between Uranus and Neptune:
  - The balance of interior heat/solar insolation/rotation in wind generation
  - The role ice “shells” and giant impacts may play in thermal evolution and interior circulation
- Implications for giant exoplanets
- Orbiters and atmospheric probes are essential

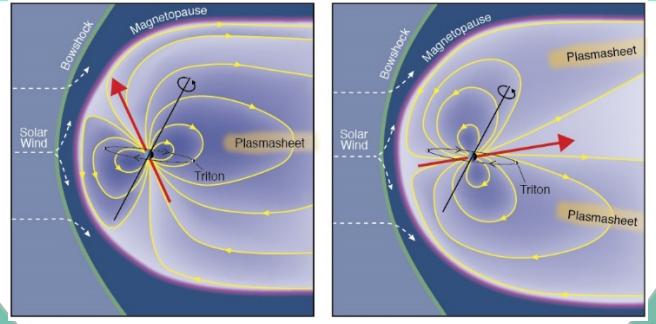


Guillot et al. Voyages 2050

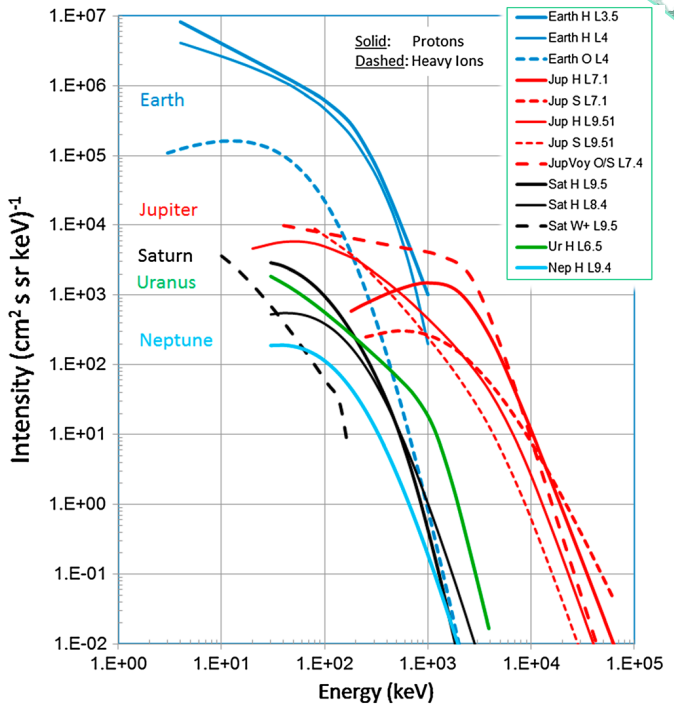


Mousis et al Voyages 2050



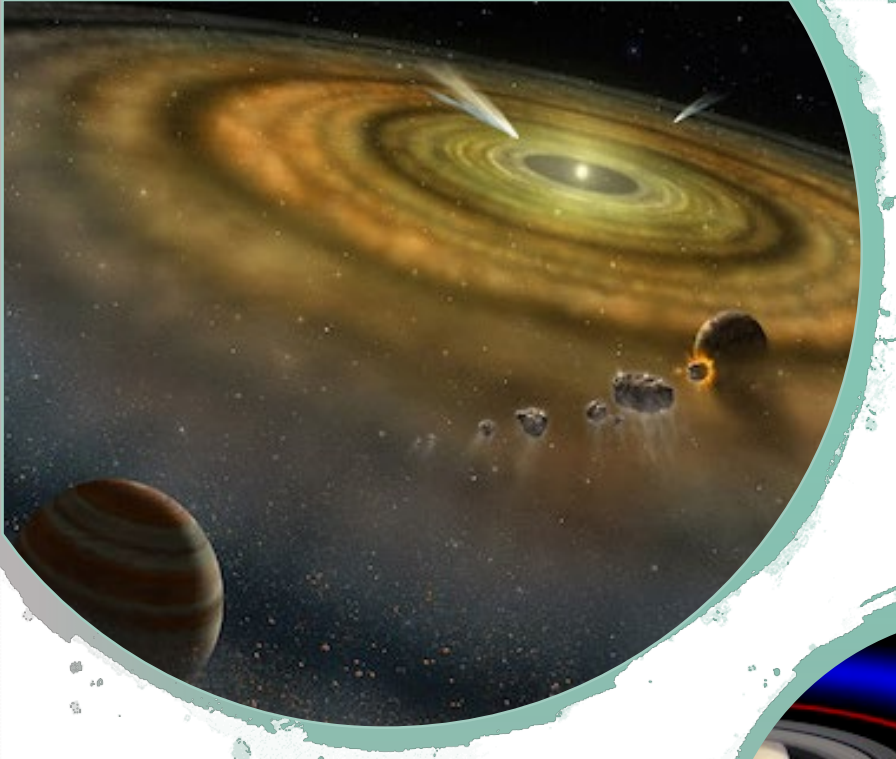


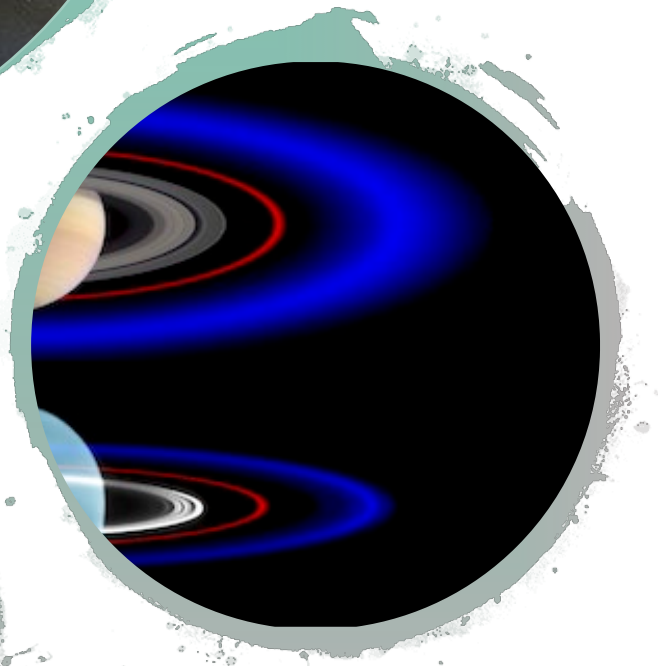
Credit: F. Bagenal, S. Bartlett

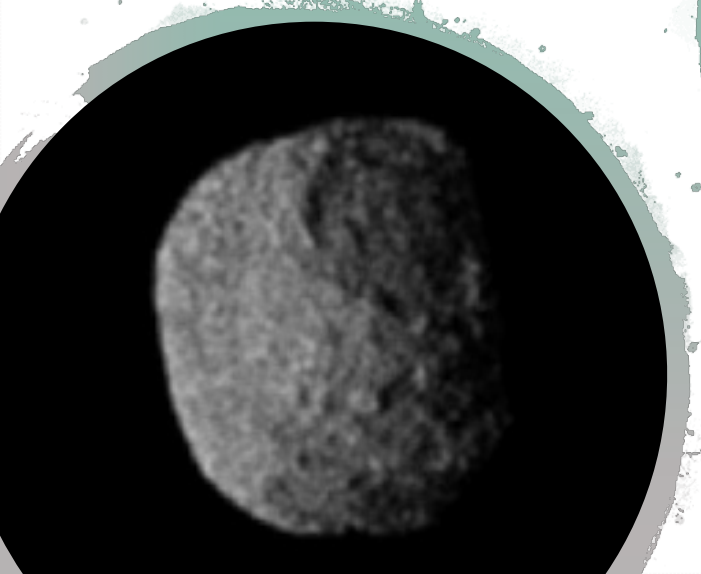


High-impact magnetospheric science

- Each ice giant has a magnetosphere that is unique in the Solar System, with its own mysteries and key science questions.
- Progress on this theme is also critical for understanding other aspects of each planetary system (e.g., atmosphere, moons).
- Fundamental magnetospheric science has implications beyond the ice giants, and beyond the Solar system.
- Orbiters with both fields and particles payload are essential.







High impact ring and small satellite science

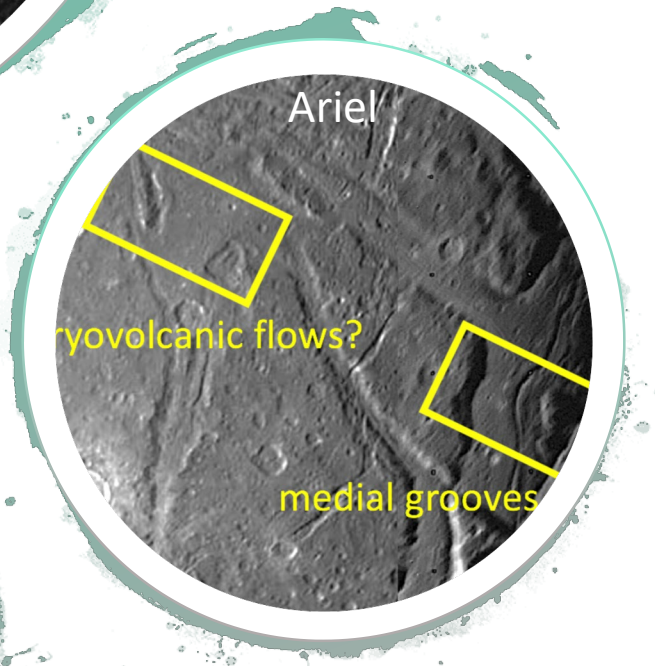
The four planetary ring-moon systems have unique properties and reveal numerous processes that we struggle to understand.

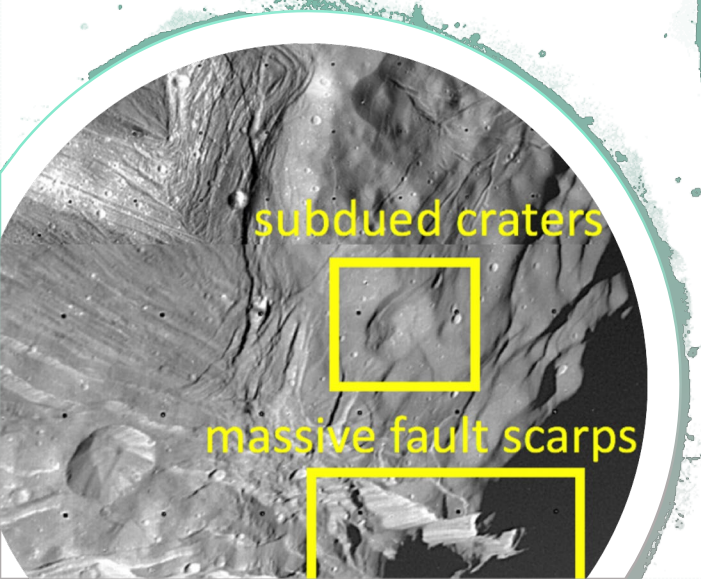
At Uranus and Neptune, we encounter:

- Short-term chaos among the moons of Uranus.
- Missing “shepherd” moons.
- Unseen source bodies for dust rings.
- Unknown arc confinement mechanisms.
- Radial oscillations that appear to arise spontaneously.

These ring-moon systems also serve as:

- Records of the collisional and evolutionary history of the planetary systems.
- Sensitive probes of planetary gravity and interior structure.
- Tracers for satellite surface properties and interiors.
- Dynamical laboratories for understanding proto-planetary and other astrophysical disks.





High impact satellite science

Possible oceans worlds now or in the past

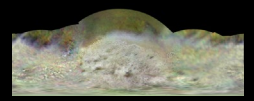
- High paleo heat flux estimates
- Possible orbital resonances in the past
- Ammonia-bearing species would lower freezing temperature

Unique surfaces and conditions that are unlike Saturnian or Jovian satellites

- Unique polygonal coronae
- Canyons with medial grooves and smooth floors
- Subdued, regolith mantled crater population
- How do longer seasons affect volatile migration?

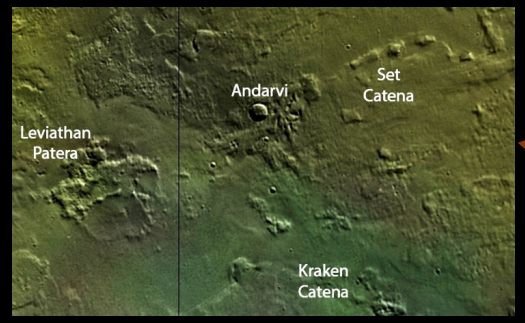
A link to the Kuiper Belt

- More similar spectrally to H_2O rich KBOs like Charon than Saturnian and Jovian satellites



High Impact Triton Science System

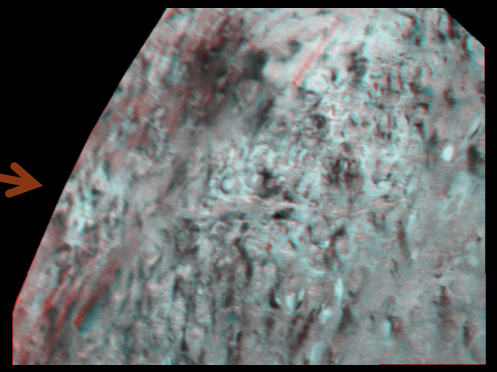
Large putative habitable world in Neptune system

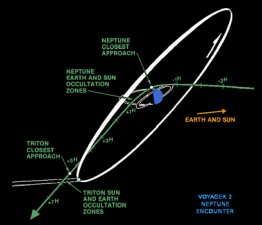


Extremely young complex geology (≤10 my? ocean related?)

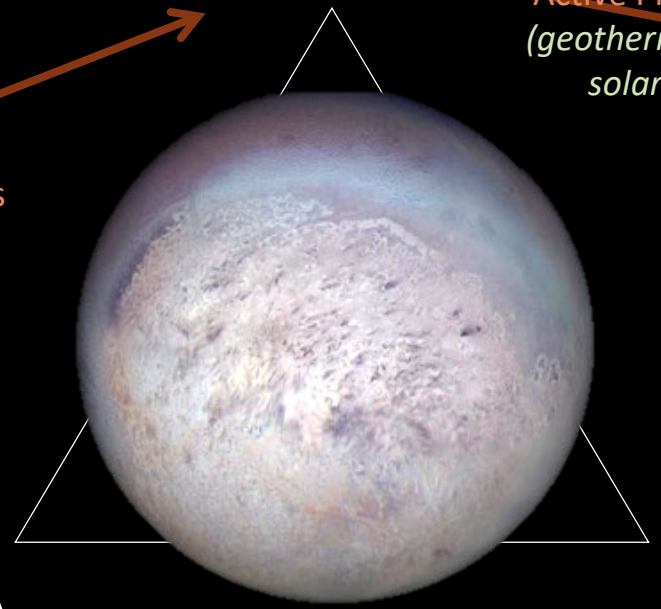
Energy (activity)

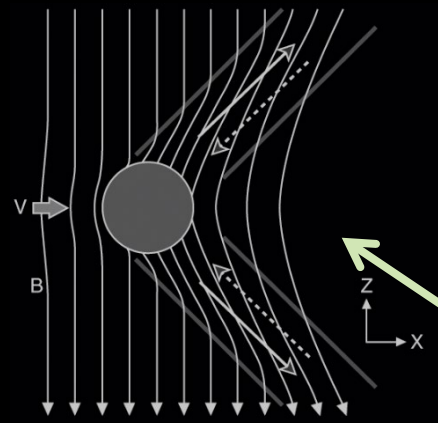
Active Plumes (geothermal or solar?)





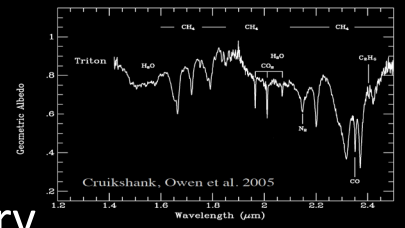
Obliquity Tides *magnitude, location?*



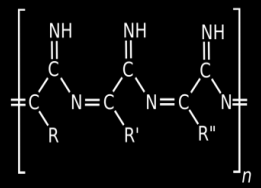


Water (ocean)

High probability *unproven, links to geology?*

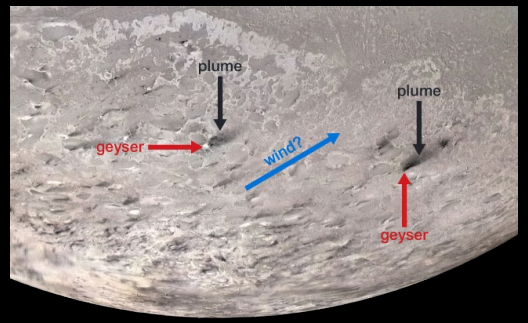


Chemistry (organics)



Surface CH_4, CO_2, C_2H_6(?)
complexity - unknown
ocean links - unknown

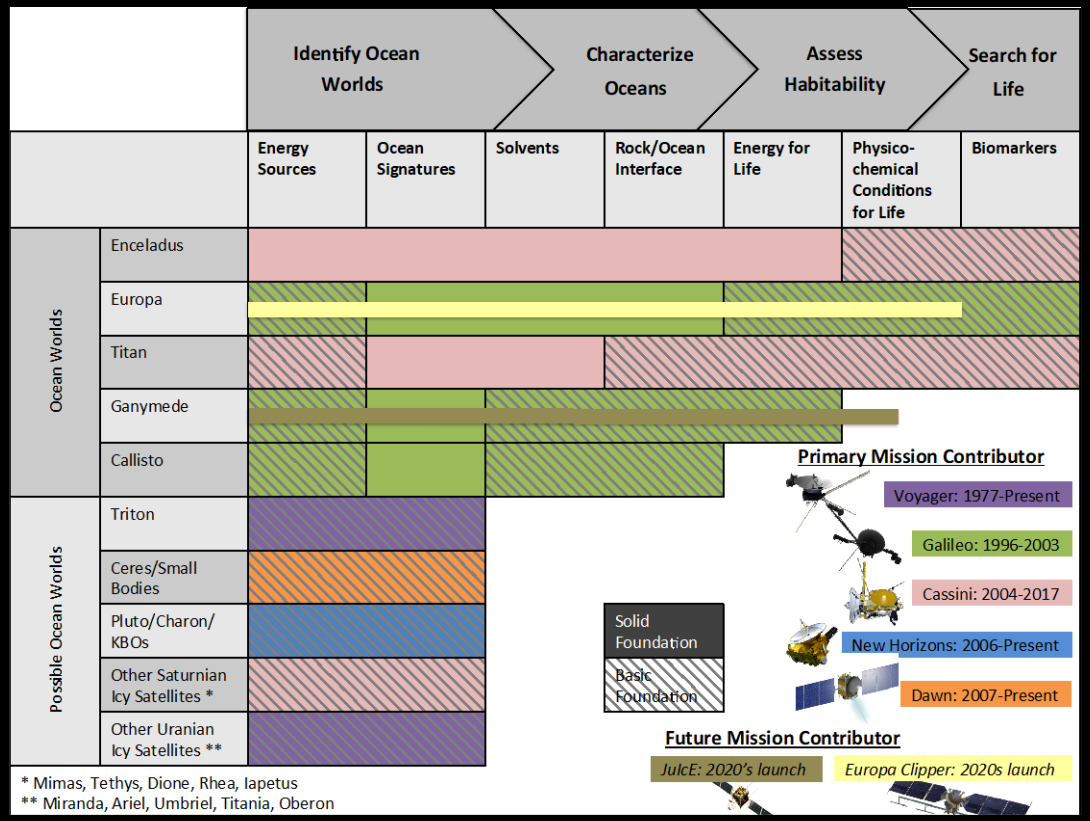
Priority Target in *Roadmap to Ocean Worlds: is there an Ocean, does it connect to surface . . .*


plume
plume
geyser
wind?
geyser

Roadmaps to Ocean Worlds

Triton as a Discovery-class next step

- Triton identified as a possible ocean world by Roadmaps to Ocean Worlds, and as a high priority mission target.
- Triton was the first of only two icy worlds with confirmed eruptive plumes; the other being Enceladus.
- If confirmed as an ocean world, and if the plumes are endogenic in nature, Triton would become one of the top targets in the solar system for life and habitability



- Triton is also one of only a limited subset of potential ocean worlds with an atmosphere supporting complex organic photochemistry.

Triton: Basic characteristics

The key ingredients to life in one distant location

- Orbit:
  - Retrograde orbit around Neptune, circular, inclined.
  - -5.88 d period
  - Average orbital speed: 4.39 km/s.
- Density: 2061 kg/m^3
- Diameter: 2707 +/- 1 km
- Albedo: 0.76
- Temperature: 38 K
- Surface Pressure: 1.4-1.9 Pa
- Water-ice world, with volatile deposits, atmosphere-surface exchange and organic photochemistry.
- Voyager 2 fly-by in 1989, before Winter Solstice (1997).