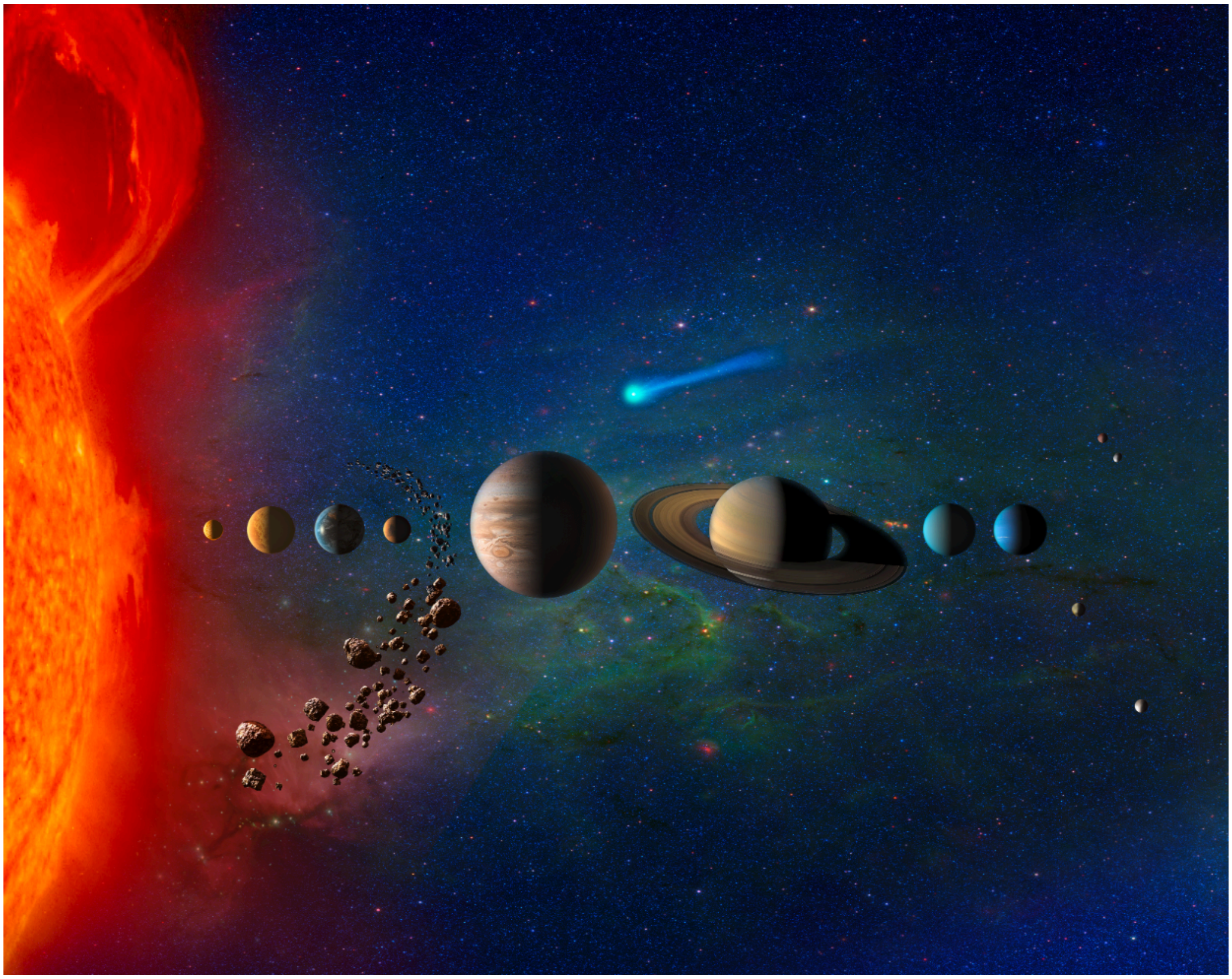
Scientific Goals for Exploration of the Outer Solar System

How did the outer planets mold the solar system and create habitable worlds?



OPAG Report

DRAFT

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Executive Summary

The purpose of this document is to frame the science objectives for exploration of the outer solar system. It is consistent with Visions and Voyages but will be kept up-to-date as 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. This document may be used as a resource for Discovery mission science objectives.

Ultimately this document will guide our preparation for the outer solar system portion of the next decadal survey.

High-level themes for exploration of the solar system are summarized in Visions and Voyages, Table 3.1, and re-iterated in the next section. But how do these themes drive us to the outer solar system? What does the outer solar system provide, that uniquely addresses our questions about origins of the solar system and habitability of icy moons? We pose the following question as the overarching purpose for exploration of the outer solar system:

How did the outer planets mold the solar system and create habitable worlds?

As stated in OPAG's 2006 Scientific Goals and Pathways for Exploration of the Outer Solar System document, the unmatched 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 – offer the opportunity to study extreme environments on comparably-sized worlds that have experienced very different geologic histories. 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 outer planets feature prominently in molding the solar system in a complex endgame that involves (a) migration of the outer two giant planets, Uranus and Neptune, from somewhere closer to the Sun to their present locations; and (b) giant planets scattering icy planetesimals into the inner solar system, delivering water and other life-critical volatile materials to the terrestrial planets.

Science *Themes*

The hierarchy of science questions in this document starts with themes from Visions and Voyages:

A. Building new worlds:
Q1. What were the initial stages, conditions and processes of solar system formation and the nature of the interstellar matter that was incorporated?
Q2. How did the giant planets and their satellite systems accrete, and is there evidence that they migrated to new orbital positions?
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?

B. Planetary habitats:
Q4. What were the primordial sources of organic matter, and where does organic synthesis continue today?
Q5. Did Mars or Venus host ancient aqueous environments conducive to early life, and is there evidence that life emerged?
Q6. Beyond Earth, are there modern habitats elsewhere in the solar system with necessary conditions, organic matter, water, energy, and nutrients to sustain life, and do organisms live there now?

C. Workings of solar systems:
Q7. How do the giant planets serve as laboratories to understand Earth, the solar system, and extrasolar planetary systems?
Q8. What solar system bodies endanger Earth's biosphere, and what mechanisms shield it?
Q9. 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?
Q10. How have the myriad chemical and physical processes that shaped the solar system operated, interacted, and evolved over time?

Themes are followed by general target goals for the gas giants, their rings, and their moons. In this hierarchy goals are followed by target-specific objectives posed as questions and referenced to these over-arching themes and questions as *Q1, Q2*, etc.

THE STUDY OF *GIANT PLANETS* AND THEIR *MAGNETOSPHERES*

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, atmospheric structure, and chemical, dynamical and other environmental processes).

Goal 2: Connections of giant planets to 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.

Goal 3: Determine 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.

SCIENCE OBJECTIVES FOR THE GIANT PLANETS

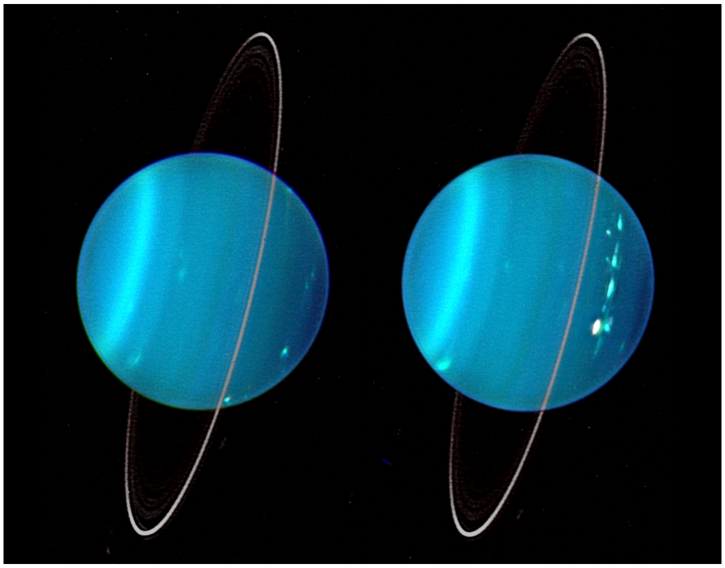
1. (Addresses Goals 1, 2, and 3): What is the interior structure and bulk composition of giant planets (including noble gas abundances and the isotopic ratios of H, C, N, and O)? [*Q1, Q2, Q3*]

Knowledge of giant planets' bulk composition and interior structure (e.g. degree of internal differentiation) are 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 the heat flow, composition, and dynamical processes acting in the observable atmosphere. Knowledge of these fundamental properties is necessary for us to understand the differences between ice giants and gas giants, the variability within each class, and to interpret how bodies of these sizes influence exoplanetary systems.

2. (Addresses Goals 1 and 2): What are the sources of internal heat, the nature of heat flow, and the radiation balance in giant planets? [*Q7, Q9, Q10*]

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 secondary internal heating processes (e.g. radiogenic, helium rain). 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. Some of the questions we hope to answer include the following. Is the low amount of internal energy being released by Uranus---an order of magnitude lower than Neptune releases---a sign of Uranus having cooled much faster (helped, perhaps, by the giant impact assumed to have knocked it on its side), or a sign of heat being trapped in the interior by a lack of convective transport? Is Helium rain-out a significant energy source on Saturn today? How do these processes influence the unexpectedly high temperatures observed in the upper atmospheres of all our solar system's giant planets, and the unexpectedly large radii of many giant planets seen around other stars?

3. (Addresses Goals 1 and 2): What is the global circulation and what are the dominant dynamical processes in giant planet atmospheres? What seasonal/temporal changes occur and why? [*Q7, Q9, Q10]*



All of the giant planets of our solar system have strong zonal winds, long-lived atmospheric features (e.g Jupiter's Great Red Spot, Saturn's Polar Hexagon, or Uranus' Berg), and short-lived weather features (storms). The abundance and distribution of trace species is indicative of meridional, longitudinal, and vertical circulation patterns. We have seen seasonal changes and longer term quasi-periodic variations on Jupiter and Saturn. Temporal variations on Uranus and Neptune are clearly seen as well, though the long orbital periods of those planets make it more difficult to distinguish seasonal from stochastic processes. 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.

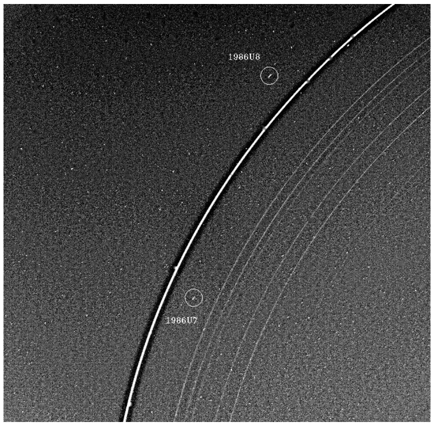
4. (Addresses Goals 1 and 2): What is the composition of giant planet atmospheres, and what are the photo- and thermo-chemical processes acting within those atmospheres (including cloud processes)? [*Q1, Q2, Q7, Q9, Q10*]

Understanding the composition and chemistry of giant planet atmospheres is necessary for understanding the current state of these planets, and provides clues about formation and evolution. For example, non-equilibrium species seen in the upper troposphere, such as PH_3 or CO, 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. A detailed understanding of chemical processes may allow us to recognize anomalies that are signs of migration of Uranus and Neptune, or residue of the giant impactor thought to have struck Uranus late in its formation.

5: (Addresses Goals 1 and 2): How do gravitational interactions drive the evolution of satellites and rings within giant planet systems? [Q1, Q2, Q7, Q10]

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. The highest-priority recommendation on rings in the 2003 decadal survey58 was accomplished: to operate and extend the Cassini orbiter mission at Saturn. Progress has also come from Earth-based observational and theoretical work as recommended by the 2003 decadal survey and others.

- 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?



6. (Addresses Goals 1 and 2): Investigate the diversity of outer planet magnetospheres

6.1 How are the internal magnetic fields of the giant planets generated? What can we learn about the interior composition and evolution of these bodies from the study of the planetary magnetic fields? *[Q3, Q7, Q10]*

The giant planets all have powerful magnetic fields generated by the convective motions of an electrically conducting interior. The magnetic field thus opens a window on the planet's interior and its evolution throughout time, providing clues that constrain the formation, thermal evolution, composition and state of the interior of each planet in the solar system. The dramatically disparate magnetic fields of the gas giant twins, Jupiter and Saturn, demonstrate how uniquely valuable the magnetic field is in diagnosing differences in state and thermal evolution of two otherwise very similar (in composition) bodies. The magnetic fields of the gas giants will be thoroughly mapped by Juno and Cassini in the coming years. Of Uranus and Neptune, we know only that they possess dynamos dramatically unlike those of the other planets, magnetic fields with poles near the equator and magnetic centers well removed from the origin. Understanding dynamo generation in these ice giants will bring us closer to an understanding of the dynamo process and the Earth's magnetic field. Planetary dynamos cannot be studied in any laboratory but for the solar system, where the experiment has been repeated for us, within bodies of differing composition, heat flow, and dynamics.

6.2 What are the properties and processes in giant-planet magnetospheres? *[Q3, Q7, Q10]*

The magnetospheres of the giant planets map out a very different environment than the one we're accustomed to, and have studied well. The giant planets provide a test of our knowledge of the processes at play in a magnetosphere and its interaction with the solar wind and internal plasma environment. Their rapid rotation, and (at Saturn and Jupiter) the introduction of mass from effusive satellites, elevates the transfer of angular momentum via current flow across field lines to paramount importance. These magnetospheres are laboratories in plasma physics, but they are also the realm within which the planet atmosphere and ionosphere interact with the distant satellites, exchanging mass and angular momentum. Jupiter and Saturn have demonstrated a great many unanticipated magnetospheric phenomena, as these planets yielded to orbital missions; one can but wonder discoveries await in the magnetospheres of two planets (Uranus and Neptune) with such unconventional planetary magnetic fields.

7. (Addresses Goal 3): What was and is the role of giant planets in creating/mitigating impact events throughout the solar system? [*Q1, Q2, Q3, Q4, Q8, Q10*]

Migration of the ice giants early in our solar systems 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. Conversely, 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. Both these mechanisms are important factors in understanding the composition of the terrestrial planets and the emergence and subsequent evolution of life. Strong enhancements in noble gas abundances for non-radiogenic components that are preferentially trapped in cold ices below 40K (e.g., neon and argon) would be a key indicator of planetary migration from the cold outer solar system.

THE STUDY OF GIANT PLANETS' *RING SYSTEMS*

Cassini is revealing a wealth of new information about Saturn's rings. Jupiter, Uranus, and Neptune all have unique ring systems and just recently, two rings were discovered around the largest Centaur, Chariklo.

Cassini has observed a wide variety of dynamical structures in Saturn's rings. Accretion is ongoing in Saturn's F ring, gravitationally triggered by close satellite passages. Non-gravitational forces like electromagnetism drive dusty rings like Saturn's E ring, Jupiter's gossamer rings, and Uranus's dusty rings. The physical processes that confine Uranus's narrow rings are a mystery—when solved this could open a new chapter in understanding ring and circumstellar disk processes. Researchers are only beginning to uncover the nature and ages of the ring materials.

From Visions 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."

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 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.

The direct detection of orbital migration remains a major goal, either for moons interacting with the rings or for embedded "propeller" moonlets, reflecting processes 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]

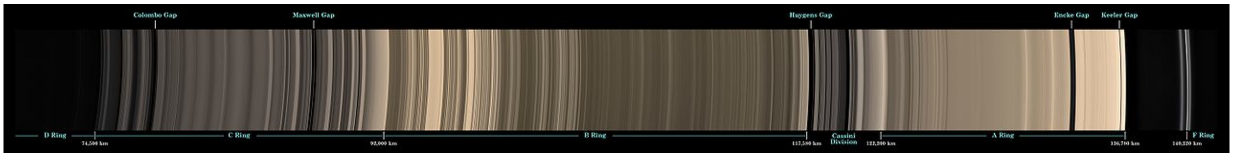


Fig. R.1: An incredible amount of detailed structure is visible in Saturn's rings.

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 Saturn system. Large planetary ring systems such Saturn's provide information on meteoroid flux and the pollution rates for the system and interconnection with the moons, important for understanding the origin 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 a well as collect dust from infalling material. Determining the ring composition and particle physical characteristics will inform our understanding of the solar system in the 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 differing origins, histories, or current states of these planetary systems?

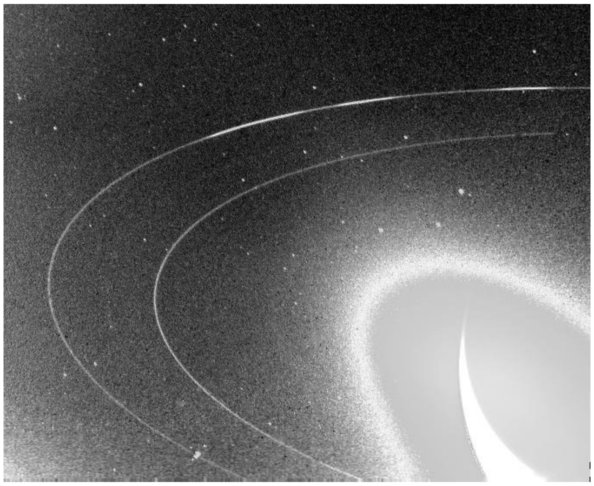


Fig. R.2: Incomplete ring arcs are seen circling Neptune in this Voyager image

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. It is the first object 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 provide windows onto the origins and operations of exoplanet systems and of or 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]

THE STUDY OF *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 record conditions from the earliest time of solar system history. The divergence as different moons became unique worlds over the last 4.5 BY is a fascinating exercise that we are only beginning to understand. The prospect that many moons may harbor subsurface pockets or oceans of liquid water raises the exciting possibility that many habitable niches exist in our solar system.

V&V Goal 1: Understand how the satellites of the outer solar system formed and evolved

V&V Goal 2: Elucidate the processes that control the present-day behavior of these bodies

V&V Goal 3: Explore the processes that may result in habitable environments

The satellite sections that follow are organized beginning with the most ***pristine and primitive*** bodies. The least evolved [e.g. Umbriel, Mimas] show no evidence for differentiation; and their surfaces are cratered at saturation. Some show volatile mobility [e.g. Callisto, Iapetus] with sputtered atmospheres and/or frost moved around on surface. Some feature surface evolution due to tectonics [e.g. Tethys, Ariel, Miranda].

Meriting their own sub-sections:
Ganymede has an evolved, differentiated interior but moderately old surface.

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

Io and ***Enceladus*** feature ongoing active eruptions and re-surfacing due to tides.

Titan, our neighborhood exoplanet, has a youthful surface with geology recognizably similar to earth (river channels, mountains, dunes) and a methane cycle analogous to earth's water-driven meteorology, with lakes, clouds and rainfall.

Europa is the current focus of our quest to understand habitable zones in subsurface oceans.

Pristine to Primitive 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 in 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 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? Laboratory work can help with interpretation of observations.
[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, Q6, Q7, Q10]

Fig.S.1: 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. 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 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 a 16-hour rotation period (current rotation period is 79.3 days). 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]

2.3 Among the mid-sized satellites, Enceladus exhibits strong evidence for a sub-surface ocean while 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, is crucial to understanding the evolution of these bodies and how materials are processed within them.
[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]

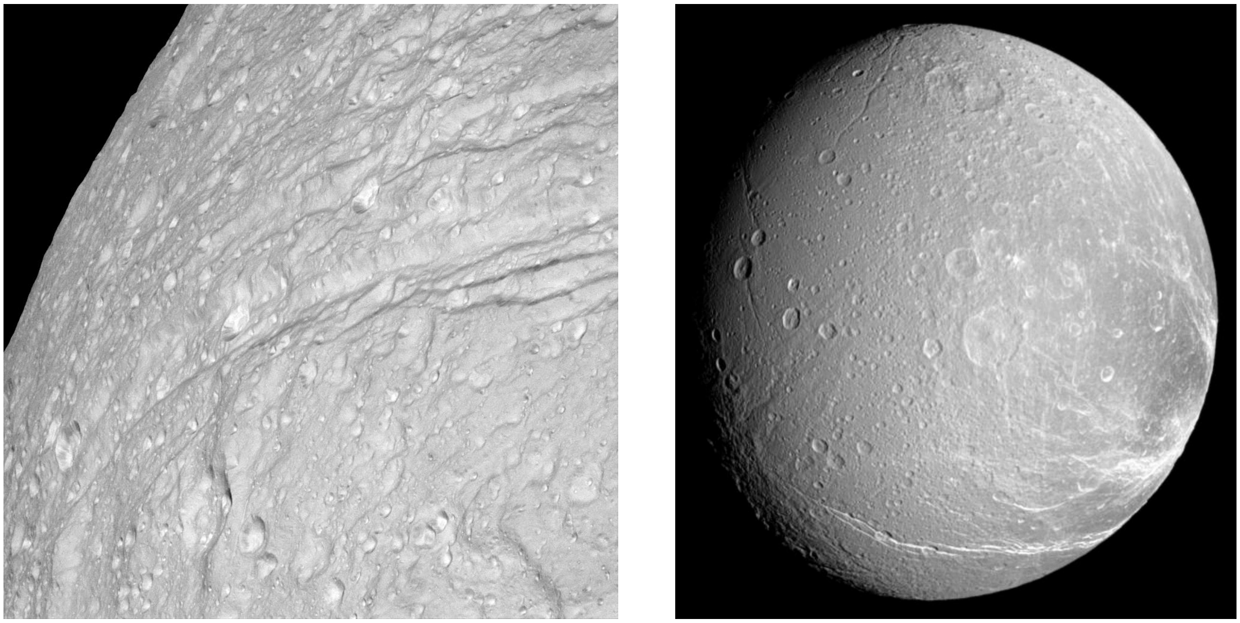


Fig S.2: Ithaca Chasma, Tethys (left) and fractures on Dione (right)

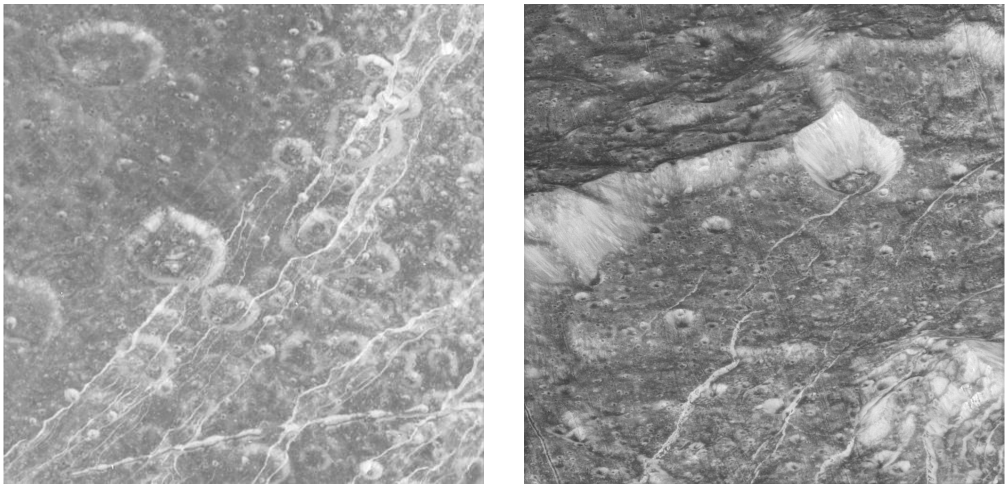


Fig.S.3: Fractures on Dione at pixel scales: 230 m (left) and 23 m (right)

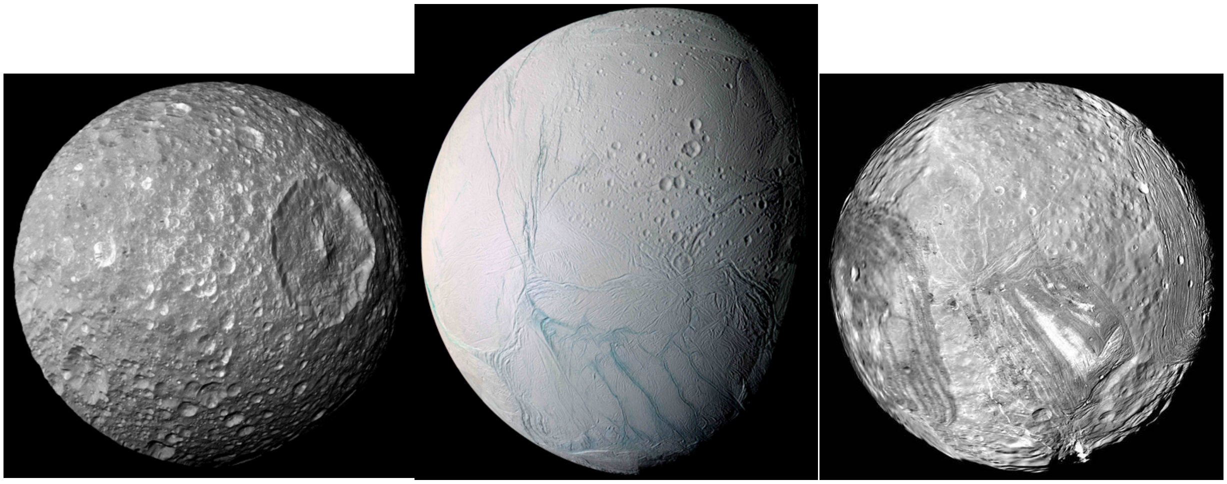


Fig.S.4: Comparably sized, vastly different Mimas (left); Enceladus, (middle), Miranda (right)

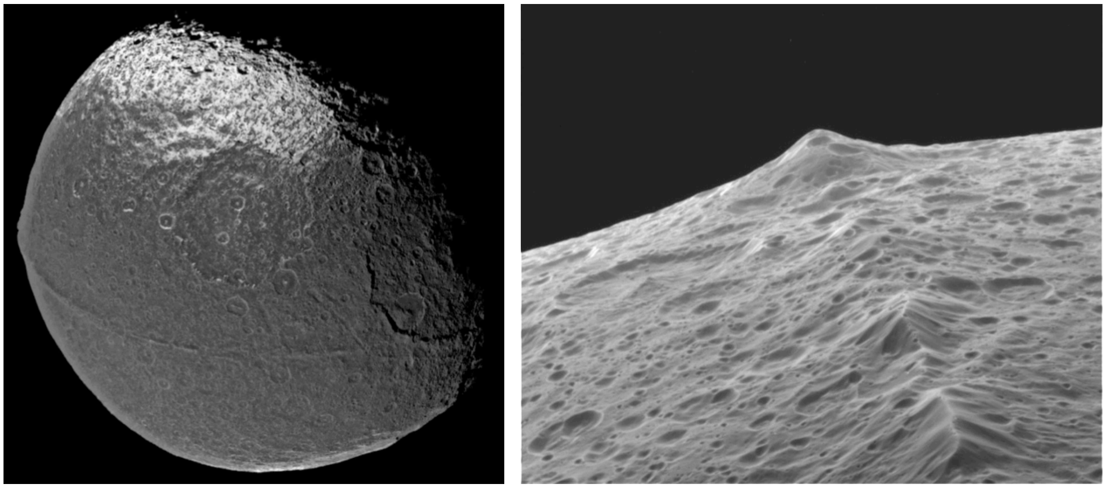


Fig.S.5: Giant impact basins and equatorial ridge on Iapetus

3.2 Cryovolcanism has been particularly difficult to identify on satellites, perhaps an indication that it occurs only rarely, 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. Intriguingly, Ariel has features that are strongly suggestive of extrusive cryovolcanism in the form of viscous flows.
[Q4, Q6, Q7, Q10]

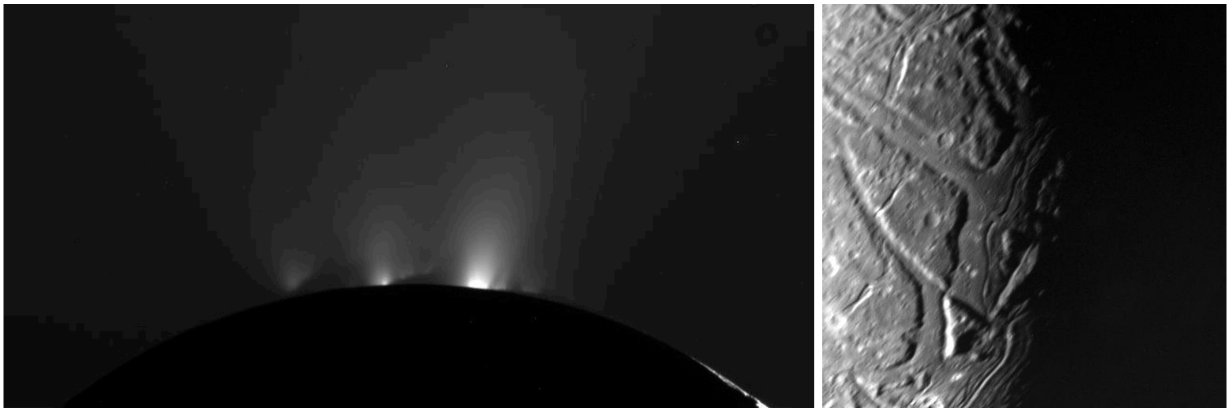
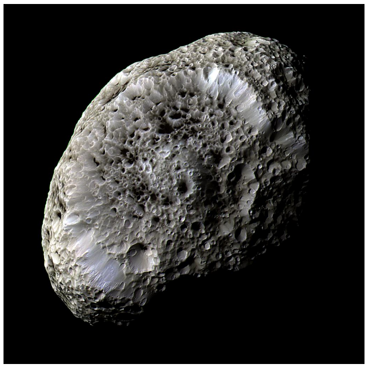


Fig.S.6: Enceladus south-polar plumes (left) and potential cryovolcanic flows on Ariel (right)

3.3 Impact crater distributions and cratering statistics have implications for understanding solar-system evolution, projectile populations temporal changes therein, and bombardment history throughout the solar system. Crater morphologies provide valuable probes of target subsurface structures and properties, *e.g.*, lithospheric thickness, heat flow, material properties.
[Q3, Q4, Q6, Q7, Q8, Q10]

4. How does solar energy affect surface processes? How is volatile re-distribution expressed?



The bright and dark surface expanses on Iapetus are the direct result of insolation-driven volatile redistribution. How has this process operated at Callisto to erode the surface and form small-scale surface topography?

Is there an insolation-driven model that can describe the evolution of Hyperion’s surface?

Fig S.7: Hyperion

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, the rheological reaction of ice and salts to stress, tides, space interactions that are still recorded in the present surface geology. The record of geological processes span 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.

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 this 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 (Bland et al., 2008, 2009). 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? And specifically, 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 (Vance et al., 2014). 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 cryo-volcanism

and or diapirism played a major role in renewing the surface? 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 largely 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 were interpreted as cryovolcanic flows.

The geologic process of resurfacing bright terrain is very poorly 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 tectonics, inferring that cryovolcanism and tectonic deformation are closely linked. 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 history than at present. *[Q10]*

3. *Surface Composition and Volatiles on the surface and in the atmosphere.* What is the chemical composition of visually dark, non-water-ice material on Europa and Ganymede? Is it hydrated salt? Could there be a component of hydrated sulfuric acid as proposed for Europa? How much exogenic material is in the Ganymede non-ice material? Is the material a single uniform composition over Ganymede's surface? What is the composition of the organic material in the surface of Ganymede and what is its origin(s)? How do the non-ice materials correlate with the surface geology, in a wide range of spatial scales? Where is the non-ice material linked to the subsurface?

To what extent is the composition and physical state altered by radiation weathering effects? What is the temporal cycle of the oxygen species on Ganymede? Is Ionian sulfur prevented from impacting Ganymede because of its internal magnetosphere? What compounds are produced through radiolytic processes on the surface of Ganymede? What are their lifetimes and rates of formation? Can their abundance and distribution inform us on the intensity and type of magnetospheric bombardment over the surface of Ganymede?

How has volatile migration affected the polar regions and why is the northern hood more prominent than the one in the south? Can the distribution of amorphosus and crystalline ice over Ganymede inform on the relative dominance of vitrification vs. thermal annealing? Are there more than one volatile involved (H_2O) in the surface material and the atmosphere? If so, what is the origin of and implication of that volatile? How do volatile inventories compare between Ganymede and the other icy Galilean satellites?
[Q9]

4. ***Ganymede's interaction with Jupiter's magnetosphere.*** **What are the characteristics of the intrinsic magnetic field of Ganymede (strength, size, variability, …)?** Where is the boundary between open and closed field lines and how does the location of this boundary relate to surface and exosphere features? What are the particle distributions of various species around Ganymede and Europa? What neutral species are present in the exospheres beyond those that have been inferred already? What are the morphology and dynamics of these weak, non-spherically symmetric exospheres? What role does Ganymede's magnetic field play in producing asymmetry there? What are the processes of production and loss of the exospheres and how do they vary in space and time? How do the exospheric particles escape and what effect do they have on the Jovian system? What is the nature of and controlling factors for the aurora on Ganymede, Europa and Io? What is the nature, structure and dynamics of Ganymede's and Europa's ionospheres? How do the atmospheres interact with the neutral and plasma tori ?

[Q10]

Triton Science Objectives

Neptune's moon Triton has only been studied by one spacecraft. Voyager flew by in southern summer and imaged just one side of Triton in high 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 rate?

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 yrs, 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?

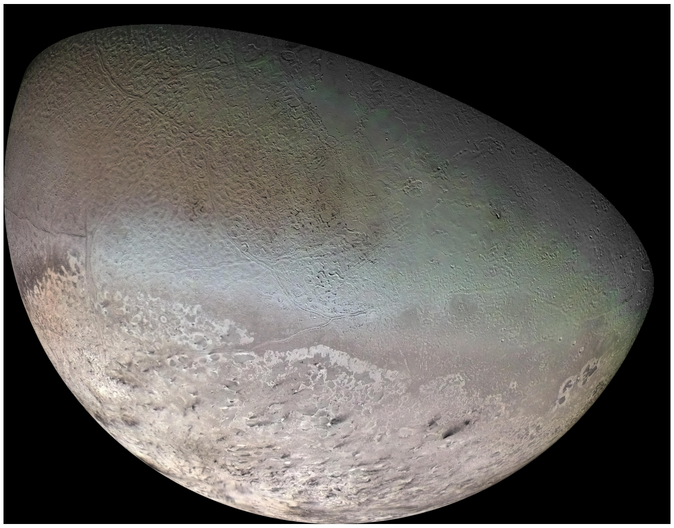
Subsurface oceans may be a common feature of icy moons, and Triton's young surface age may be indicative that it too has a subsurface ocean.

If Triton possesses an internal ocean, is it 'perched' (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 helio-centric 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 <100 MY is derived from the lack 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 Enceladus – other moons with active surface 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 interations 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?**

The compositions of Triton's individual surface units are unknown because Voyager did not have an near-infrared spectrometer, and ground-based observations have limited spatial resolution.

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?

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 occurrence tell us about the energetics, relevant processes, and the nitrogen reservoir?**

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.

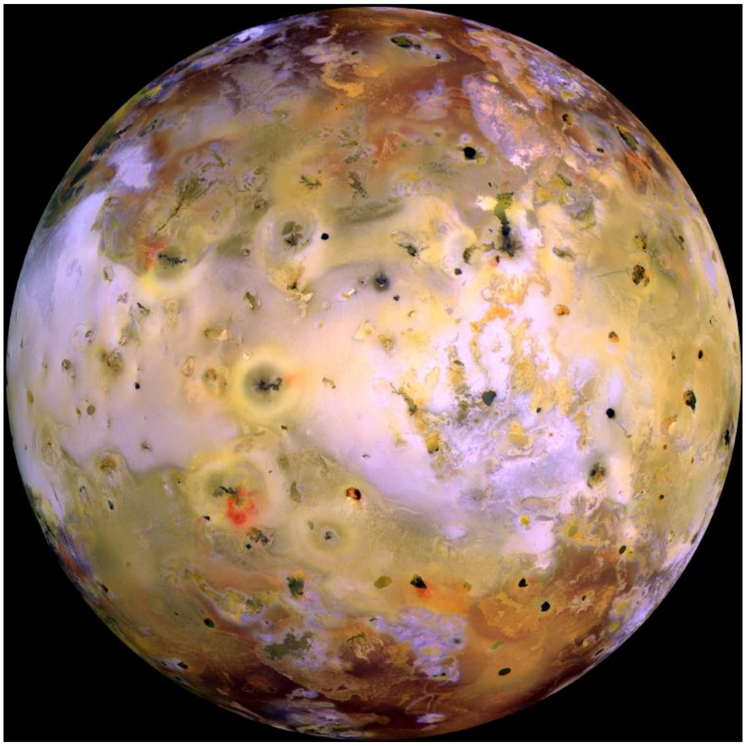
If endogenic the plumes may be sampling a subsurface ocean; similar arguments apply to recent cryovolcanism. These would be important for understanding Triton's internal heat flow and tectonics, and would add Triton to the list of key astrobiological targets. *[Q6]*

5. Triton's interaction with Neptune's magnetosphere. **How does 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?**

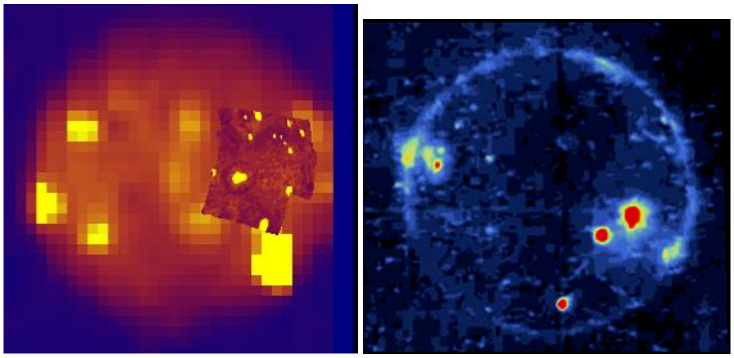
How is the relatively dense neutral torus of Triton formed, and what is its relationship to loss processes from Triton's atmosphere? Voyager radio science observations revealed a significant ionosphere with a well-defined peak at ~350 km altitude; however, the distance and the geometry of the Triton closest approach precluded in situ observations of either the ionosphere or its interaction with Neptune's magnetosphere. *[Q10]*

Io Science Objectives

Jupiter's innermost Galilean satellite, Io, is extremely active on the surface, in the interior, and in the exosphere. There are more active volcanoes per unit area than on any other body, including Earth, and these volcanoes connect to the tidally worked interior and to the atmosphere and Jupiter environment. Understanding the processes that lead to the generation and consequences of volcanic eruptions will inform studies of Europa and the other Galilean satellites, Jupiter and the magnetosphere, and volcanism and tectonism throughout the solar system.



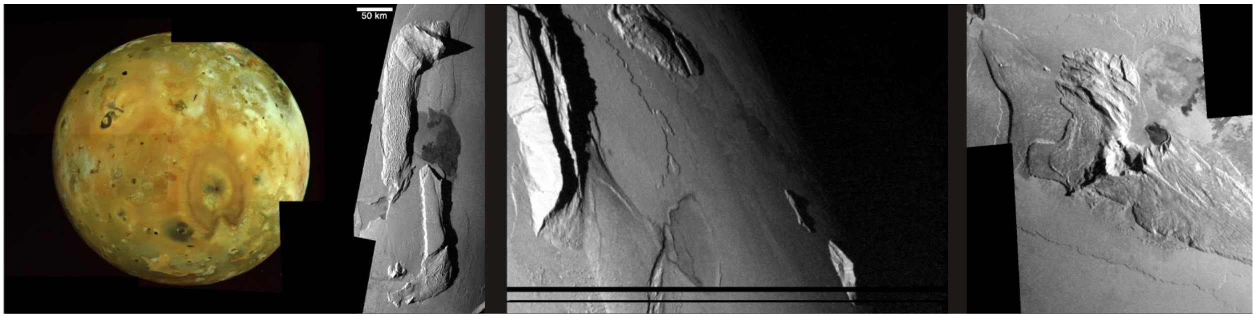
1. What are the processes that control Io's volcanic eruptions and how do they vary spatially and temporally?

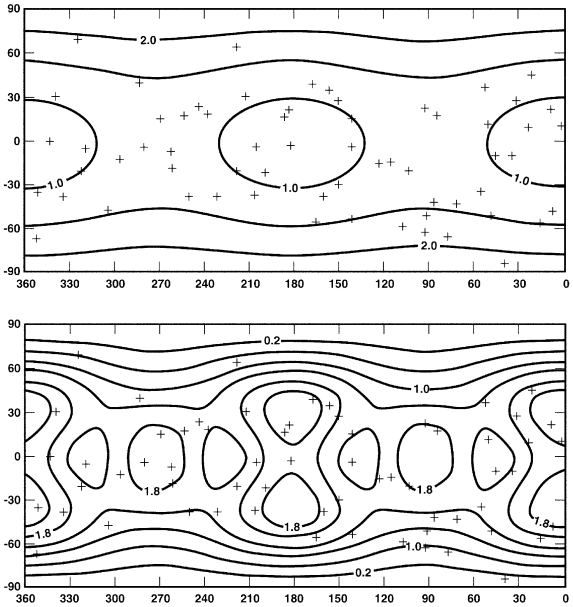


Over one hundred active volcanic centers have been identified, yet the generation of the volcanoes, the style and duration of eruptions and connectivity between volcanic centers are poorly understood. Furthermore, it is not known what their compositions are or if the eruption type at a single location changes with time. In addition,

minor volcanic types that are sulfur or SO_2 dominated have been suggested, but their extent is unknown.
[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?

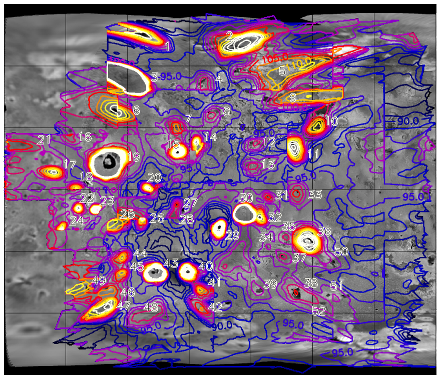




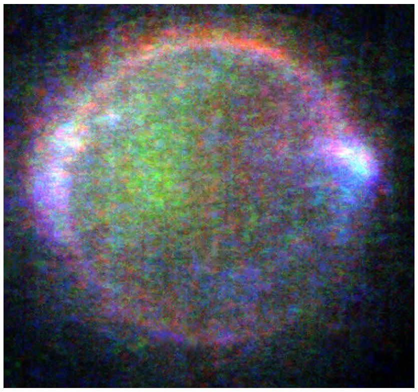
There are more than 100 mountains on Io, the majority appearing to be tectonic, rather than volcanic, structures. There is no obvious global pattern to their locations; with the exception of a bimodal distribution with longitude and while mountains have local associations with paterae, globally there is no 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 (volcano-tectonic depressions), have yet to be discovered. It is also unknown whether the nature of the process has changed with time. 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]*

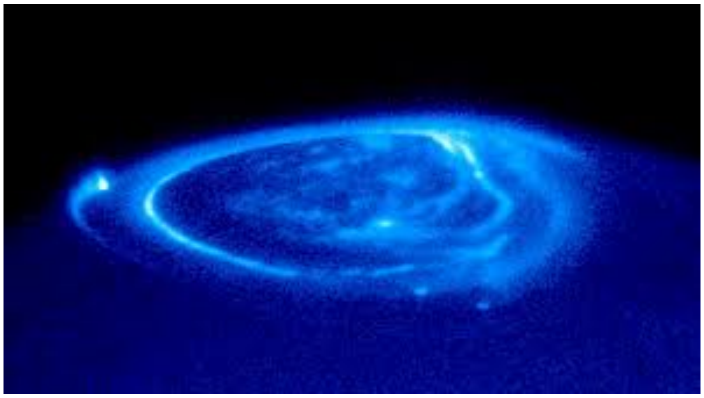
3. What are the magnitude, spatial distribution, temporal variability, and dissipation mechanisms of tidal heating within Io? How is heat transfer to the surface controlled by internal structure? What is the internal structure (temperature, composition, deformation), is there a magma ocean and what is its nature?

Io's extremely active volcanism is explained by excessive amounts of internal tidal heating. Measurements of Io's heat flow from ground-based telescopes and Galileo PPR data are around 2 W/m^2, more than twice as large as the upper limit expected for steady-state tidal heating models, yet how this has affected Io’s interior and surface is still unknown. Comparisons of spatial variability in Io’s volcanoes to tidal heating models show that the distribution of hotspots is more consistent with the heating occurring in the asthenosphere rather than the mantle. Magnetometer data from Galileo suggest the presence of an interior magma ocean, yet how large or deep this ocean 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. What is the temporal and spatial variability of the density and composition of Io’s atmosphere, how is the variability controlled, and how is the atmosphere affected by changes in volcanic activity? How does the atmosphere affect the state of the Io torus, the Jovian magnetosphere, and aurorae?





Io’s atmosphere appears to be controlled by both volcanic emissions from Io’s near-surface and deep interior and sublimation of surface volatiles. However, which process is dominant is not yet known and has implications for the vertical and thermal structure of the atmosphere, its lifetime and composition. 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 interactions between Io’s volcanoes, atmosphere, neutral cloud, and torus are complex and have implications for the entire Jovian system. [*Q2, Q6, Q7, Q10]*

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 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 most importantly, what is the thickness and extent of any subsurface ocean or sea?

Gravity models are *consistent* with at least a regional sea at the south pole and a large, low density (~2500 kg/m^3) core. But is the sea global? Whatever its extent, any subsurface sea or ocean should be more directly confirmed.

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' orgin. 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 workers?

[Q1, Q2, Q10]

2. *Composition of Enceladus' Ocean.* What is the composition of the ocean, sea, or liquid reservoir that apparently feeds the plumes erupting from the South Polar Terrain? How does this composition relate or map to in situ mass spectrometer and dust or other measurements of plume vapor and solid particles?

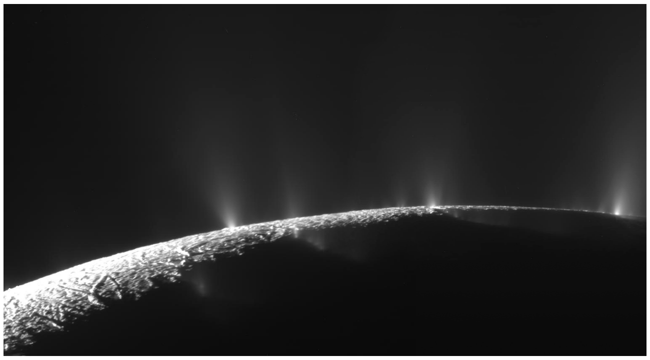
Are ammonia, methanol, chloride or bicarbonate salts, or some other materials, depressing the melting point and enabling a liquid water layer or changing rheological properties within Enceladus' solid ice shell?

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 seen in Cassini INMS 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, freeze/thaw 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 are 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 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' on Enceladus, but is there 'CHONPS,' and are other elements bioavailable? What energy sources are potential available for life? And what lessons from Enceladus apply to Europa, and visa versa?

Finally, given the availability of water, at least some biogenic elements, and tidal energy, there is the simple question: is there extant life on Enceladus?

[Q6]

Titan Science Objectives

Titan, the largest satellite of Saturn, larger than the planet Mercury, has the most Earth-like surface of any other planetary body, and a nitrogen-based atmosphere more massive than our own. There is active rainfall and erosion that creates rivers, lakes, seas, eroded landscapes, and vast fields of sand dunes. The Titan environment is rich with complex organics 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 antigreenhouse effects. Underlying all this is a Callisto-sized icy satellite undergoing tidal flexing and thermal evolution.

Goal 1: Explore surface and interior processes

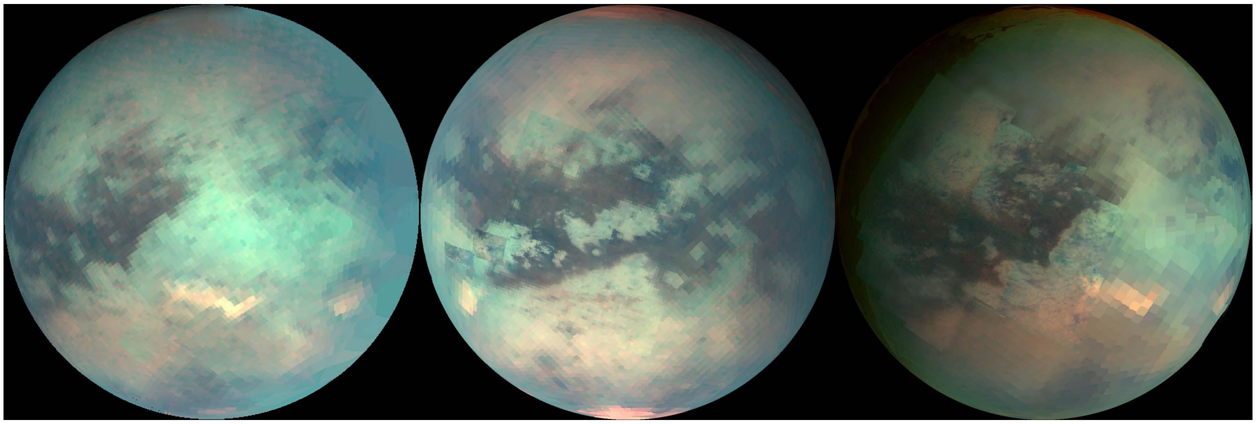
Explore the processes active on the surface and in the interior of Titan and how these processes are related to Titan's history and composition, and relate them to similar processes on Earth and other solar and extrasolar planets.

Goal 2: Investigate change in the atmosphere and surface

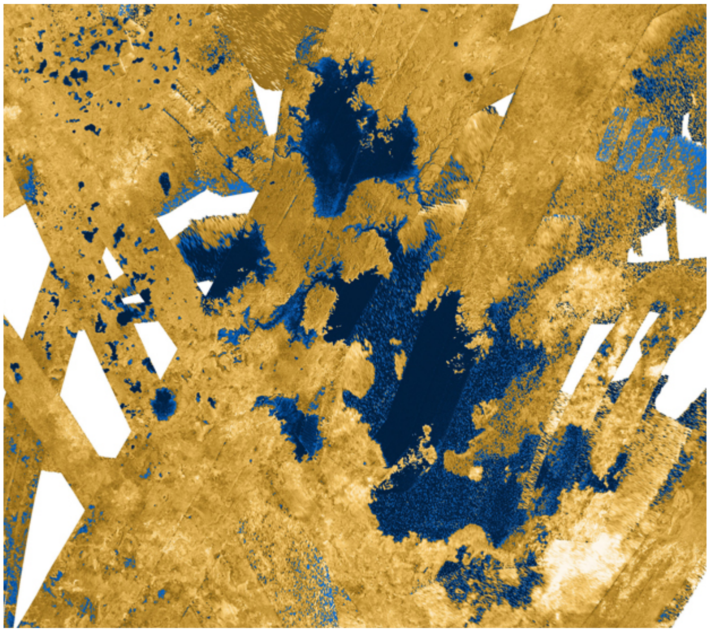
Investigate how and where change occurs on Titan today as a result of orbital and internal variations, as a means to help us understand similar processes and activities on Earth and other planets.

Goal 3: Determine habitability

Investigate the surface and subsurface oceanic compositional and environmental conditions of Titan and determine if they have been amenable to the rise or life, or its molecular precursors.



1. (Addresses Goal 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 belt, 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 named 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. Obtaining methane and ethane fluids to enact the surface erosion 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. (Addresses Goal 2): How and when do changes in Titan's atmosphere occur, and how are these expressed at the surface?

Seasonal changes are thought to occur in Titan's atmosphere, based on studies of the 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 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. This 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. (Addresses Goals 1 and 2): 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 the size and tidal energy present, as well as the young surface, more internal differentiation would be expected. New studies show there could be more differentiation 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 lithospheric tectonism and volcanism. In addition, understanding the release of volatiles from the interior, such as ammonia and methane, which aids differentiation and volcanism, is important. Studies of tectonism and volcanism on Titan also helps us understand the communication between the liquid water ocean at 50 km depth below the ice lithosphere and the organic-rich surface, which has astrobiological implications. [*Q2, Q3, Q7, Q10]*

4. (Addresses Goals 1, 2 and 3): 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 up in Titan's atmosphere leads to the formation of long-chain organic (C-H based) molecules. While some compositions have been determined, such as ethane, hydrogen cyanide, propane, butane and acetylene, and many other higher-mass hydrocarbon and nitrile compositions, the details of 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, have yet to be determined. In addition, oxygen from Enceladus has the potential to form amino acids from the nitriles in Titan's atmosphere. These organic molecules in Titan's lakes, on the beaches and in the rivers have the potential for prebiotic and biotic processes. Yet where these processes could occur, under what chemistries, and at what rates is not yet known. [*Q2, Q6, Q7, Q10*]

5. How can Titan inform us about extrasolar planets?

An extrasolar planet similar to Titan in size and effective temperature would orbit a typical M-dwarf star at around 1 AU, where tidal locking, coronal mass ejections, flares, and inefficiency in volatile delivery during formation are not of concern. Around the smallest M-dwarfs, this distance would shrink to 0.2 AU, but even were we to disregard these, 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 is a good guide.

Europa Science Objectives

Europa is among the most promising candidates in the search for life beyond Earth due to its young surface, energetic environment and potentially rich inventory of ingredients for life that has existed over the lifetime of the solar system. Among the icy satellites of the outer solar system, Europa is also in a special position: having been visited by both Voyager and Galileo, hypotheses regarding Europa are vastly more mature than for other bodies. If the NASA mantra of "fly-by, orbit, rove, and return samples" is the path forward, Europa lies toward the "lander" edge of this spectrum. Because of what we know already, there are many detailed investigations of merit for Europa. However, it is what we don't yet know…and what we wish to that inspired the following five fundamental topics that define Europa science for the coming decades.

1. How does Europa's ice shell work?

Europa's surface is riddled with fascinating geology, and scarce on craters. The surface, with an estimated age of 40-90 Ma, must be recycled or reprocessed in order to explain observations of its surface. How does this happen? At present, while the preponderance of evidence suggests an ice shell thickness of at least 10 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 have 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 arcuit 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 though 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 motion. Cycloids have been suggested to occur due to diurnal variations in tidal stress ("tidal walking") or due to tidal stress plus additional non-synchronous and 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 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 due to either stresses of ice shell thickening, ocean overpressure, or dike formation propagating cracks through the shell. However, these 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. New work considers that the combination of tidal and convective stresses may play a role in the formation of these features. However, with only 6 close flybys of Europa by Galileo data, as yet no convincing evidence in any particular direction can eliminate the field of possibilities.

Europa's bands—wide, relatively flat and variegated linear bands of generally darker or newer ice—are regions of presumed production of new surface material, and destruction of old material. These regions may accommodate some of the compressional stress that must accompany the predominantly extensional ridges. Thought to be perhaps analogous to seafloor spreading centers on the Earth, these features are however poorly 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. Recent work tantalizingly suggest that 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 formation mechanism for these features is highly debated, but all involve formation in the presence of shallow liquid water, and thus these features are amongst Europa's most compelling. 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, 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.

These features, along with Europa's sparse cratering record and their superposition, 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 layers, potentially creating a conveyor belt of material through the shell. Since the ice shell is the mediator of 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.

2. What is the interior structure of Europa?

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

However, with only 6 close flybys of Europa, both the magnetic field and gravity data are low resolution. For instance, the depth 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 detect the intrinsic field that may be generated. 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.

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 intrinsic 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 that these could extend through Europa's ice shell is unclear. Many of Europa's surface features are likely 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 or thermo-compositional processes, rather than direct communication with the ocean. However, in this case ice rising from the ocean interface would be rapidly mixed with shallow ice via melting, so the distribution of water within the shallow ice is also provocative. Since future landers may be capable of landing near these features, understanding which are water rich will be critical to future exploration as these are the easiest water bodies to reach.

Geological data are inconclusive as to the depth of the ice shell. Assumptions can be grouped into two classes: thick and thin, the former with estimates ranging from 10 to 30 km and the latter 3-5 km. This is an important constraint to have 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, leaving little energy to be produced within Europa's rocky layer—thus potentially allowing any internal activity on the moon to shut down. 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 core.

Water plumes have been suggested by several lines of evidence, including Europa's variable oxygen atmosphere and contribution to the Jovian magnetosphere, and by analogy to other active satellites such as Enceladus. 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 in the southern hemisphere—though not the south pole—could be the source of water ejected into the Europan exosphere. With only a single set of observations, 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.

4. What is Europa's surface, ocean, and interior composition?

In addition to geologic heterogeneity, Europa's surface is also compositionally variable. Both Voyager and Galileo data showed that the surface is a mixture of dark material within the background ice, but the detailed composition is heretofore unknown.

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 the magnetic field sputtering the surface. 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 authors. Earth-based telescopes suggest similar results. However, whether this represents processing of ocean material, or a mixture of exogenic and endogenic materials, is debated. This material may provide clues to the habitability of Europa's ice shell and ocean.

Based on limited magnetospheric data, Europa's ocean is likely similar 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 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 mostly anoxic 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 planet'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? Has the core fully reacted with the ocean, or might such processes as serpentinization and dehydration still be underway? The density of Europa's 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 core is mostly hydrated, or if it is fully differentiated, would provide insight into the activity of Europa's interior over time.

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 question of habitability. For Europa, this can be broken down into several key components: Does Europa possess the necessary ingredients for life? Did it ever? And if so, has life ever arisen on Europa? In order to be habitable, as we currently understand it, water and biologically relevant compounds (iron, phosphorous, 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 still unknown, but these important considerations represent a maturing picture of what it means to be habitable. This is of course, related but separate from whether life originates at all.

The four questions above motivate the questions of Europa's past and present habitability. As a small body, 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 initiate habitability early on. This activity manifests itself as both surface geology and putative sea floor activity. It is likely that in order to be habitable, Europa's surface, sputtered by the Jovian magnetosphere and bathed in particles from the Io Taurus, must be recycled on a rapid enough timescale to deliver biologically relevant oxidants and probably phosphorous 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 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. Compelling new work describes how planetary environments may be necessary geochemical precursors for life as we know it, and other work suggests that it is life that changes the system to match its needs. This field of study generally centers on either surface or deep ocean systems as possible locations for the origins of life—where hydrothermal vents in an anoxic ocean set up energetic reactions that could build precursor geochemical systems, or surface pools of water where hydration, dehydration, and the possible introduction of exogenic or endogenic materials creates the conditions for life. An origin of life on Europa, at such a great distance from Earth, likely would represent the chance to close, 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 unhabitable, or uninhabited, it may well be that the moon once was a stable place for life. Uniquely from places such as Mars where origins 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 this answer, and a life detection would truly change the way we think about astrobiology, planetary science, and even life on Earth.

Coming soon: sections on technology development and lab experiments