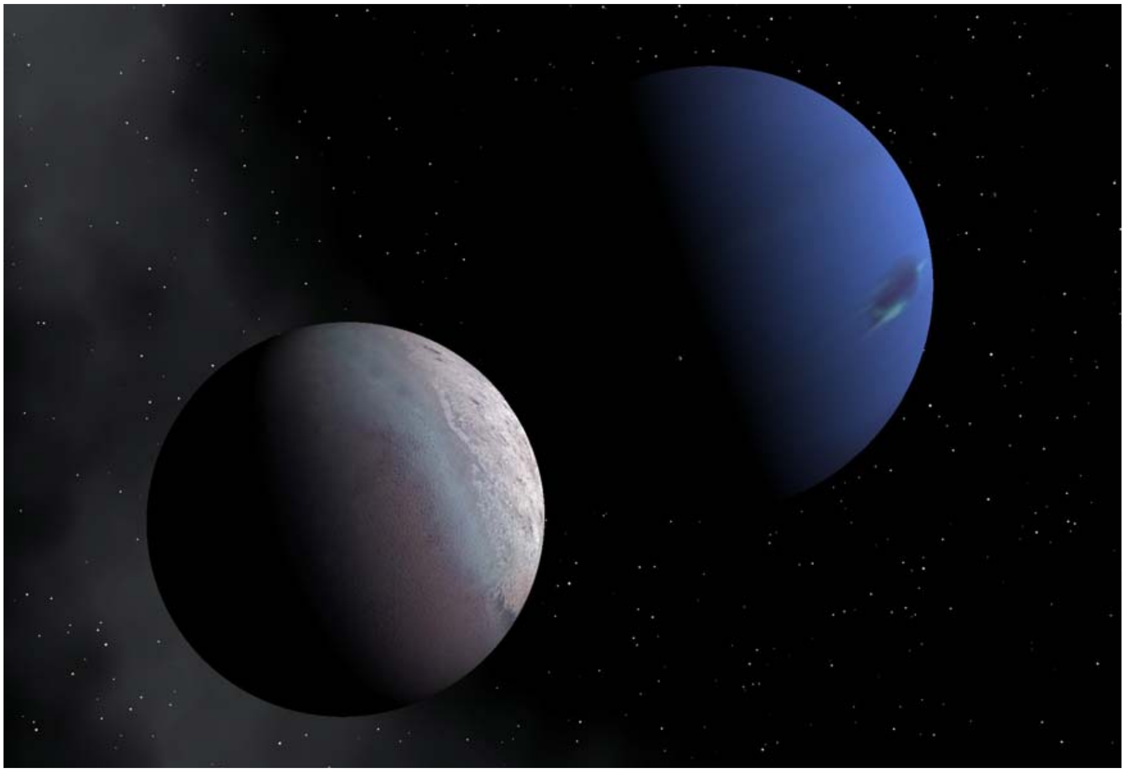
The Exploration of Neptune and Triton



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1. EXECUTIVE SUMMARY

Neptune and its captured moon Triton are unexplored with modern spacecraft instrumentation. Observations of these objects are urgently needed to address planet formation and the evolution of ice giant planets, icy satellites, Kuiper Belt Objects, and the solar system itself.

Neptune has the strongest winds in the solar system, a highly complex magnetosphere, tenuous ring arcs and a system of satellites that has suffered extreme collisional, tidal, and orbital evolution. The composition and size of its core constrains planetary formation at the edge of the planetary system, and informs the characteristics of the system's subsequent dynamical evolution.

Neptune's large moon Triton is likely a captured Kuiper Belt Object (KBO), with a remarkable but poorly understood surface and atmosphere that hint at geological activity, an active interior, and a possible subsurface ocean. Due to its unique dynamical history, Triton possesses both properties known to drive interesting geology and chemistry on icy worlds: hydrocarbons and a history of tidal dissipation. Thus, Triton holds the key to understanding the evolution of the entire spectrum of icy objects in the solar system, from large icy moons to small KBOs.

A Neptune orbiter, which may be feasible under the New Frontiers program given recent technological developments, would provide a significant increase in scientific knowledge at modest cost. However, new measurements returned by any class of mission would contribute priority science.

Science goals for the system include:

- Determine the existence and depth of an ocean on Triton, and characterize its cryovolcanism
- Characterize Triton's surface chemistry
- Characterize the composition, structure, and dynamics of Triton's atmosphere
- Better characterize the range of ages of Triton's surface units
- Determine the size of Neptune's core
- Characterize the composition, structure, and dynamics of Neptune's atmosphere
- Determine how energy and particles flow throughout Neptune's complex magnetosphere
- Constrain the structure of Neptune's ring arcs and properties of its irregular satellites

We recommend that a Neptune mission become a community priority for the next decade. A Neptune system orbiter or flyby should be included in the target list for New Frontiers. A Flagship should also be considered. Any class of mission would return priority science of value to the entire planetary science community.

2. MYSTERIES OF NEPTUNE

2.1 Formation and Dynamical Evolution

The nature and origin of Neptune are crucial to understanding the formation and evolution of the solar system. The gas giants Jupiter and Saturn are constrained to form during the solar system's first few million years while the protoplanetary gas disk was present. But the timing and location of the formation of Neptune is relatively unconstrained. Neptune's mass is large enough to undergo 'runaway' gas accretion in the solar nebula ($\geq 10\ M_{\oplus}$). However, the moderate gaseous component suggests that its formation was not yet complete when the gaseous nebula dissipated. Theoretical efforts to understand Neptune's formation have led to quite divergent models of its mode and timescale of formation (Lissauer et al., 1995; Kokubo & Ida 1998, Goldreich et al., 2004); the formation of Neptune may have involved large-scale orbital migration of the giant planets (Fernandez & Ip 1984; Malhotra 1993, 1995).

The early dynamical evolution of Neptune is tightly coupled to neighboring populations and may play a central role in determining the orbital architecture of the giant planets (Tsiganis et al., 2005), creating and sculpting of the Kuiper Belt (Hahn & Malhotra 2005; Levison et al., 2008) forming irregular satellite systems (Nesvorny et al., 2007), and causing a period of intense bombardment of the terrestrial planets early in Solar System history (Gomes et al., 2005).

<u>Key Questions</u>:

- How did Neptune form?
- What is Neptune's composition and internal structure?
- Where is Neptune's dynamical birthplace, and how did it migrate to its current location?
- How are ice giant satellite systems influenced by planetary formation conditions?

2.2 Atmosphere and Interior

The structure and dynamics of the ice giant atmospheres are among the least understood in the Solar System. The higher bulk abundances of ices such as methane and lower solar input relative to other planets are first-order differences in the chemistry and boundary conditions that drive atmospheric dynamics. However, the 3-dimensional compositional and dynamical variations of the atmosphere at local scales are unconstrained except for a single, IR-blind *Voyager* flyby. Studying the structure and dynamics of an ice giant's atmosphere with a level of detail unobtainable from Earth, and extending wavelength coverage to include the UV and IR, will provide critical data on the least-explored type of planetary atmosphere in the Solar System.

Characterization of Neptune is needed both to understand its evolution in the Solar System and to provide a basis for understanding ice giant extrasolar planets. Several extrasolar planets with masses comparable to Neptune have been discovered (e.g. so-called "Hot-Neptunes") with more discoveries imminent as detection methods improve and the *Kepler* mission begins its survey.

<u>Key Questions</u>:

- What is the size and mass of Neptune's core?
- What processes drive the strong atmospheric dynamics of a planet so far from the Sun?
- What is the three-dimensional structure and composition of the atmosphere?
- Why is Neptune warm relative to Uranus, the other ice giant in our solar system?

3. MYSTERIES OF TRITON

3.1 Origin

Triton is likely the only large satellite in our Solar System that did not form *in situ* around its host planet. Triton's inclined and retrograde orbit suggest that it was captured by Neptune at some point in its history (McKinnon 1984; Goldreich et al., 1989; McKinnon et al., 1995; Agnor & Hamilton 2006). Thus, Triton probably formed in the protoplanetary nebula as an icy dwarf planet and may have a composition similar to other large primitive bodies such as Pluto, Eris, Sedna, Ceres, and Vesta.

Triton's post-capture orbital evolution is suspected to have put it on a collision course with any existing inner satellites, leading to large-velocity impacts that generated significant debris. Triton itself may have accumulated a significant portion of its mass (>20%) from this debris (Cuk & Gladman 2005). The accretion of this material could have hastened Triton's orbital decay and raises the possibility that it may be a composite of heliocentric and planetocentric material. As Triton's orbit decayed, tidal heating dominated its orbital and thermal evolution. The heating during this epoch is likely to have been sufficient to yield global melting of Triton and the formation of subsurface oceans (McKinnon et al. 1995).

Key Questions:

- What does Triton's chemistry tell us about its origin?
- What is the range of ages of Triton's surface units?
- What is the current heat flow rate from Triton?

3.2 Interior, Geology, and Atmosphere

Triton's mass and density lie between those of Pluto and Europa. *Voyager 2* images of Triton's surface revealed a young surface containing landforms unlike any others seen in the solar system including "cantaloupe terrain", active "geysers", and long linear features which may be similar to Europa's double ridges (Prockter et al., 2006). Many of Triton's surface features may be cryovolcanic in origin (see Croft et al., 1995), and are likely formed by the same complex interaction between tidal dissipation, heat transfer, and tectonics that drives resurfacing on Europa, Ganymede, and Enceladus. However, *Voyager's* limited coverage and spatial resolution prevents us from unraveling Triton's geological history.

Since the *Voyager* encounters, subsurface oceans have been detected in the three icy Galilean satellites Europa, Ganymede, Callisto, and *Cassini* data gives indirect evidence for oceans in Enceladus and Titan (Zimmer et al., 2000; Kivelson et al., 2002; Schubert et al., 2007; Lorenz et al., 2008). There is mounting evidence that subsurface oceans may be common in icy moons. The composition of Triton's surface is mysterious because *Voyager 2* did not have a near-infrared spectrometer (Brown et al., 1995). Determining whether Triton has an ocean, and whether any of its oceanic chemistry is expressed on its surface or in its atmosphere should be a high scientific priority. Triton's geysers (identified in *Voyager 2* flyby data) and significant nitrogen and hydrogen atmosphere put Triton into the rare class of moons with a substantial atmosphere and active geology. Studying Triton's geysers and atmosphere would provide clues on interior composition, and provide a key comparison to Pluto, and to other KBOs that may have atmospheres. Finally, Triton's internal energy source and possible liquid ocean make it an attractive astrobiological target for exploration.

Triton is subject to the tidal, radiolytic, and collisional environment of an icy satellite, but with the initial composition of a KBO. Indeed, Triton's duality as both captured dwarf planet and large icy satellite that has experienced extreme collisional and tidal processing, make it a unique lens for understanding two of the Solar System's principal constituencies and the fundamental processes that govern their evolution. Thus, comparisons between Triton and other icy objects will facilitate re-interpretation of existing data and maximize the return from prior NASA missions, including *New Horizons* results about the Pluto system, *Galileo* and *Cassini* observations of the Jovian and Saturnian satellites, and *Dawn* observations of Ceres and Vesta.

Key Questions:

- Is Triton presently active? How active?
- What is the source of energy for the plumes?
- Does Triton have an ocean today, or could it have had one in the past?
- How was Triton's complex geology influenced by tidal forces and chemistry?
- How is Triton's surface and interior chemistry expressed in its atmosphere?

4. MYSTERIES OF THE NEPTUNE SYSTEM

4.1 Magnetosphere and Satellite-Magnetosphere Interactions

Neptune provides an appealing and uniquely complex laboratory for the study of space plasma processes, and particle and field interactions with planets. Its magnetic field is highly tilted, has substantial non-dipolar contributions, and is offset from the planet's center, challenging theories for its formation (e.g. Connerney et al., 1991; Stanley & Bloxham, 2004). The magnetosphere reconfigures itself from Earth-like to "pole on" with every rotation, and charged particles in the magnetosphere follow complex paths, creating highly structured aurora and radio emission (e.g. Schulz et al., 1995; Sandel et al., 1990; Zarka et al., 1995). Triton's hydrogen and nitrogen atmosphere is a main source of Neptune's magnetospheric plasma, dominating the middle-magnetosphere (e.g. Summers & Strobel, 1991; Eviatar et al., 1995). Particles and fields in the magnetosphere, in turn, interact with Triton's atmosphere, surface, and perhaps a magnetic field from a possible subsurface ocean (Hoogeveen & Cloutier, 1996; Ruiz, 2003).

Voyager 2 spent about one Neptune-day inside the magnetosphere, so we do not understand how the Neptune magnetosphere varies temporally, and whether or how it varies with longitude (Richardson, 1993). Existing magnetic field models are poorly constrained because there are very few magnetic field measurements close to the planet where non-dipolar field contributions are most easily measured. These models are critical to understanding Neptune's deep interior, aurora and airglow, complex radio emission, and charged particle motion close to the planet. *Voyager* passed quickly by Triton, so could not adequately characterize the interaction of Triton's atmosphere and ionosphere with Neptune's magnetic field under a variety of magnetospheric configurations.

Key Questions:

- What are the interior processes that create Neptune's complex magnetic field?
- How are particles and energy transported in a highly structured magnetic field?
- How and in what quantity does Triton/Neptune/solar wind add magnetospheric plasma?
- Does Triton have aurora, a global intrinsic or induced magnetic field, or a plasma torus?
- Does Neptune have lightning?

4.2 Neptune's ring arcs and small bodies

Neptune's dark and dusty ring system expresses the best-developed set of arcs in the Solar System (see e.g. Porco et al., 1995 for a review), yet are poorly understood. It differs fundamentally from Saturn's dramatic system, Jupiter's small satellite-derived rings, and the narrow, dusty ring system of Uranus. The ring arcs' composition and association with the small moons is nearly completely unknown. Their particle-size distribution, a key property for understanding their evolution, is also poorly constrained. The mechanisms responsible for confining and maintaining narrow ring arcs (e.g. Porco 1991), uniquely expressed at Neptune, have only become more mysterious since the *Voyager* era as Earth-based follow-up observations have been unable to confirm early models (Dumas et al., 2002). Variability further complicates the issue, as processes apparently acting within the rings cause significant changes on short time scales (de Pater et al., 2005). As ring systems are in some respects a dynamical analogue to proto-planetary disks, developing a deep knowledge of the diverse formation and evolutionary styles of ring systems helps us understand the conditions and processes of early planetary formation.

The last decade has seen the discovery of new groups of irregular satellites at each of the giant planets. In addition to 340-km Nereid, Neptune is now known to retain at least six irregular satellites (Holman et al., 2004). These rogue satellites are likely to be the last objects permanently captured by Neptune, with their origin and evolution tightly coupled to Neptune's orbital migration and Triton's tidal and collisional evolution. Like Triton, these captured primitive bodies may have originated in the Kuiper Belt. A flyby of Nereid (or another Neptunian irregular) would provide a wealth of new clues and constraints on Neptune's history, information on the collisional and dynamical processing of captured satellites, and possible information about the formation conditions, locations, and evolution of KBOs.

A return to Neptune with modern CCD imagers, and their vast improvement in spatial, spectral, and temporal capabilities relative to *Voyager 2*, would provide an opportunity to study and understand Neptune's ring system and its unique set of arcs in detail. Long-term observation of the rings at close range may identify periodicities and the dynamical signatures of the processes responsible for the ring arcs and other structures. Refining the orbits of Neptune's small regular moons and possibly discovering new ones would help clarify the relationship between Neptune's satellites and the ring system's structure and composition.

Key Questions:

- What are the source and sinks of Neptune's ring arcs and how are they confined?
- What are the structure, dynamics, and composition of the rings, and how do they evolve?
- Are the regular satellites fragments of a previous population or aggregates of debris?
- Are Nereid and the other irregulars captured KBOs?

5. FEASIBILITY

In the two decades since the *Voyager 2* flyby of Neptune, and in the three decades since the *Voyager 2* instruments were designed and built, there have been significant advances in instrument technology. Greater sensitivity, energy ranges, and resolution are now available in visible imagers, IR and UV spectrometers, and particle and field instruments. A suite of these instruments on a Flagship mission would follow in the revolutionary footsteps of the *Galileo* and *Cassini* missions, but that **does not** imply a Flagship mission is the only worthwhile platform for exploring the system. A smaller subset of those instruments, on a New Frontiers orbiter could address multiple first-order questions. For example, an imager, a magnetometer, and an ultra-stable oscillator (for precise navigation and measurement of gravity moments) would address fundamental questions on the geology of Triton and the interior and atmospheres of both Neptune and Triton. A New Frontiers flyby, equipped with a more comprehensive instrument suite, could capture unprecedented data on Neptune and Triton's compositions (using IR and UV spectrometers), interiors (using gravity and/or a magnetometer), and atmospheric dynamics (long-term imaging prior to encounter), structure and evolution of Neptune's ring arcs (long-term imaging prior to encounter), and surface geology and activity of Triton (imaging). A Discovery-class flyby, even with just a small instrument suite (e.g. an imaging spectrometer and a charged particle detector), would return invaluable data.

Now that the launch vehicle available for the New Frontiers and Discovery programs is from the highly capable Atlas family (with a much greater lift and throw capacity than even the Delta II-H), high mass or high velocity launches are possible. The trade between a New Frontiers flyby vs. orbiter is in the cost to implement and operate the instrument payload: a flyby could carry a larger payload, but offers a single encounter; an orbiter provides a longer duration mission period within the system, but would be restricted to a smaller payload. Several missions (e.g. Stardust before it became Stardust-NExT, New Horizons) have implemented infrequent-Earth-contact "hibernation" modes, demonstrating low-cost, long-cruise missions are possible.

The fundamental enabling technology for a Neptune system mission, regardless of mission class, is radioisotope power. The next Discovery round, in which two Advanced Stirling Radioisotope Generators (ASRGs) will be provided at no cost to the mission (if an ASRG-enabled mission is selected), provides an excellent template for expanding Discovery-class missions to the outer solar system. For example, if it is decided that half of the Discovery opportunities be RTG-enabled, a Discovery-class mission to Neptune becomes feasible.

6. CONCLUDING STATEMENTS

Neptune and Triton offer a host of unanswered yet profound questions regarding the nature and evolution of the solar system. A return to Neptune for *in situ* measurements with modern instruments would represent a major gain in solar system science by opening a new class of worlds, ice giant planets, to detailed exploration. Such a mission would provide comprehensive opportunities, cross-cutting the interests and disciplines of the entire planetary community: atmospheres, interiors, magnetospheres, geology, ring systems, primitive bodies, icy satellites, dwarf planets and dynamics. Further, it would enhance the science return from previous missions (e.g. *Galileo, Cassini, New Horizons, Dawn, Juno, Kepler*) by fostering comparative study between bodies (e.g. Pluto and Triton, Saturn and Neptune) and re-interpretation of previous datasets.

For these reasons, Neptune and Triton have previously been recognized as 'first-priority' targets for exploration by the planetary community (2003 Decadal Survey, OPAG Pathways document). New theories about the early evolution of the solar system (e.g., Tsiganis et al., 2005) and the discovery of numerous dwarf planets in the Kuiper Belt further underscore the importance of the Neptune system to planetary formation and diversity, and accentuate the need for further detailed exploration. However, we do not have a credible near-term opportunity to return to Neptune and Triton with spacecraft. The next decade must provide that opportunity.

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