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Exploration of the Neptune System

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Abstract. We propose a mission to the Neptune system comprised of an orbiter with a Neptune atmospheric multi-probe. NASA's Solar System Exploration theme listed a Neptune mission as one of its top priorities for the mid-term (2008-2013). A recent NASA study also gave it top ranking for rich scientific return and connections to astrophysical problems outside the Solar System (atmospheric structure and dynamics, geology, ring systems/dynamics, magnetic fields/dynamos, pre-biotic chemistry on Triton, local extrasolar planet analog for Neptune- and Uranus-sized objects), calling it "almost Cassini-like in scope, near Discovery-like in cost" (though the costing was admittedly done in more optimistic times). The Neptune mission's unmatched diversity of science yield should place it at the top of the queue for outer planet exploration.

EXECUTIVE SUMMARY

Our knowledge of the Neptune system has been developed in three phases. The first, from 1846 to 1989, was based entirely on Earth-based observations. Then in 1989, the Voyager 2 flyby revolutionized our understanding of the Neptune system. The third phase, from 1989 through to the present, HST, Keck, NASA IRTF, other ground-based observatories have continued to probe Neptune and its environs, revealing that much more remains to be learned about this system.

In spite of (perhaps due to) Voyager's success at Neptune and subsequent studies with HST, many questions about Neptune remain, and we identify what is needed to answer them. What powers the winds, and why are the winds and thermal structure similar to those of Uranus, though the internal heat sources differ? How deep does the zonal structure go? For these, we need visible imaging and thermal mapping at various phase angles with scales down to 10 km occultations of radio telemetry signals to probe atmosphere down to $\sim$2 bar. What is the composition of discrete features (bright and dark), and of the atmosphere as

a function of altitude? UV occultations to measure density, scale height, temperature and composition, and compositional mapping at near-IR wavelengths would address this. Why are the magnetic fields much more asymmetric in ice giants than in gas giants? This question requires measurements of magnetic field and magnetospheric particles at a variety of latitudes and longitudes.

Short of exploring Pluto, exploring Triton may provide our best opportunity to examine the surface and atmosphere of a Kuiper Belt Object analog. What is Triton's atmospheric composition and structure, and how has it changed since Voyager? To answer this, we need radio occultations to determine atmospheric size/structure, high phase and high-resolution (100-300 m) limb imaging for hazes/plumes, UV occultations (density, scale height, temperature, composition), and atmospheric sampling (fly-through). Is there evidence for "recent" solid-state convective activity in an icy mantle? How does composition vary between/within surface features? What causes geologic structures on Triton's surface? Has the geyser distribution changed since Voyager? Have atmospheric changes modified the surface? To answer these questions requires UV to near-IR global imaging ($<$ 100 m), high-resolution imaging (10-30 m) of selected locales, thermal (50 and 100 μm) mapping, and global 1-km imaging spectroscopy at 1-5 μm with $\lambda/\Delta\lambda = 300$.

Is a resonant model for arc stability correct? If not, how do arcs remain stable? Do Neptune's inner satellites show the effect of extreme tidal stress? Are they a "major ring system waiting to happen"? To better understand the Neptune ring system, we need low-phase 100-m scale imaging of arcs to find embedded bodies, high-phase 1-km scale imaging to detect new rings/arcs and to characterize ring/arc morphology, and spectroscopic capability to determine composition.

We divide our recommendations into two categories: interplanetary spacecraft and activities that can be performed on or near Earth. Among all of the possible activities that we considered for the coming decade, our overall number one priority is for a robust program of technology development for deep space missions, of which a Neptune System mission should be a flagship. Of almost equal importance is continued support of the Earth-based and future near-Earth observational programs for the Neptune System (planet, rings, and Triton).

If new discoveries come from exploring those areas where our ignorance is deepest, then the Neptunian system clearly offers the greatest potential for expanding our knowledge. Bringing our understanding of the Neptune system up to a similar level as the (Galileo) Jupiter and (expected Cassini) Saturn systems would greatly enhance the ability of the planetary community to do meaningful comparative studies. We should also consider the fact that some day in the not-so-distant future, astronomers will discover Neptune-sized bodies around other stars. Having a more complete understanding of our own Solar System's ice giants will be invaluable for providing context for the study of extra-solar ice giant planets.

Our top priority among potential missions is a Neptune System Orbiter. Given the technological advances since the Voyager 2 Mission, a flyby would yield excellent scientific return. However, an orbiter could significantly enhance the science: long-term coverage of atmospheric dynamics on Neptune, the opportunity for multiple high-resolution mapping passes for Neptune and Triton

to measure small-scale and short-term changes, coverage over a wide range of phase angles for multiple targets (atmospheres, surfaces, rings).

The orbiter is the core of the mission, providing a remote sensing platform, in-situ probes of the magnetic field and environs, and primary data links. Multi-probes are an essential part of an investigation of the deep ($\sim$100 bar) atmospheric structure and chemistry on Neptune. However, significant technology advances would be required to enable high S/N transmission from depth in a cost-effective manner.

Recent studies indicate a Neptune System mission is feasible given innovative technologies (Porco 1998): high-power lightweight SEP and solar sails, qualified aeroshells, aerocapture, autonomous spacecraft communications, advances in miniaturization, lightweight power generation systems, temperature-tolerant electronics ($\sim$50 K), and lightweight structures. These technology drivers are required for many outer planet missions.

After an orbiter mission, our next priority is a Neptune flyby mission. An orbiter is strongly preferred for reasons outlined above, but a flyby would produce excellent scientific return. Given the cost constraints of the current political situation, a flyby merits discussion.

The main spacecraft would carry a remote sensing platform, in-situ probes of the magnetic field and environs, and primary data links. As with an orbiter, multi-probes should still be considered for a flyby mission, and can be an essential part of an investigation of Neptune's deep atmospheric structure and chemistry.

In the category of Earth-based and Near-Earth activities, our top priority recommendations are moving target capability on future space-based telescopes, e.g., NGST) and access to existing and future large telescopes for planetary system observations (e.g., IRTF and NGST). High priority recommendations are long-term observing campaigns for the atmosphere of Neptune and the reflectivity of Triton, and laboratory experiments at temperatures and pressures relevant to the Neptune system. Priority recommendations are a long term observing campaign for the rings of Neptune, periodic astrometric observations of Neptune's inner satellites, and improvement in models and simulations pertinent to issues in the Neptune planetary system.

REPORT

Neptune serves as an extra-solar planet analog. Triton serves as an analog KBO and provides ties to pre-biotic chemistry via surface organics (ring particle composition may also be of relevance). We have already revisited Jupiter and (soon) Saturn, which are (fraternal) twin gas giants, so a visit to an ice giant would be timely. Furthermore, smaller extrasolar planets will soon be detected. Sub-Saturn-sized are already detected, and it is only a matter of time before Neptune-sized bodies are detected. A comprehensive understanding of such bodies in our own solar system should therefore be of top importance to NASA, and this is in fact reflected in the ranking of such a mission in recent NASA reports (Table 1).

During the preparation of this white paper, we assumed that a mission to Pluto is in the NASA queue. Pluto and Triton are an excellent pair for compara-

Table I - Importance of Neptune System Exploration to NASA

Date	Comment	Source
1998	Very high scientific priority	SSES Astrophysical Analogs Campaign Strategy Working Group Report
1999	Top priority	Exploration of the Solar System, Science and Mission Strategy (SSE Roadmap)
2000	Important component of post-2007 exploration	NASA Space Science Enterprise Strategic Plan
2000	High-level roadmap: contribution to national priorities (2012-2025)	NASA Strategic Plan 2000

tive planetological studies. A Pluto mission finishes the job of the Voyager era of initial exploration; a Neptune system mission is part of the Galileo and Cassini era of more in-depth studies. We strongly support a Pluto mission. We also ruled out a Uranus system mission because of timing. Uranus is approaching equinox right now (2007). By the time a spacecraft could be planned, launched, and had traveled to Uranus, the planet would probably be well past equinox and approaching northern solstice. Since this is the same season that Voyager observed, the atmospheric observations would likely be far less interesting that those of Neptune. A series of missions to Centaurs, KBOs, and the Uranian system could, taken together, perhaps provide extensive information about giant planet atmospheres, small outer solar system bodies, rings, and magnetospheres, but only in the Neptune system are all of these fascinating areas of investigation available in a single system.

1. Current State of Knowledge

Based on size and heliocentric distance, the four giant planets in our Solar System break neatly into two pairs. The Gas Giants, Jupiter and Saturn, consist of a deep, massive atmosphere of gases such as hydrogen and helium surrounding a small core of rock, water, and ammonia. Both have been the target of intensive study, most recently with Galileo (for Jupiter) and with Cassini (for Jupiter and soon Saturn). Further out lie the smaller giants Uranus and Neptune. The term Ice Giant is now being used more frequently to characterize these planets, which consist mostly of a core of "ices" – of water, methane, and ammonia – surrounded by a moderately thick atmosphere of hydrogen and helium.

Our knowledge of the Neptune system has been developed in three phases. The first, from 1846 to 1989, was based entirely on Earth-based observations. Then in 1989, the Voyager 2 flyby revolutionized our understanding of the Neptune system. The third phase, from 1989 through to the present, HST, Keck, NASA IRTF, and other ground-based observatories have continued to probe

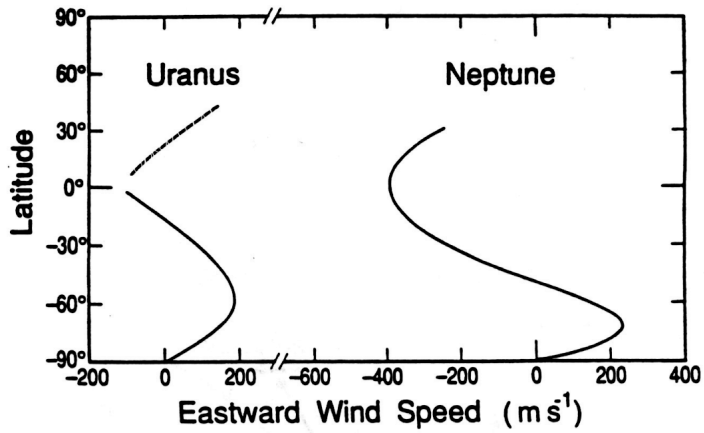

Figure 1. Comparison of zonal wind profiles of Uranus and Neptune. Adapted from Ingersoll et al. (1995) with Uranus data from Hammel et al. (2001).

Neptune and its environs, revealing that much more remains to be learned about this system.

1.1. Neptune

Atmospheric dynamics and structure: The major development in our understanding of Neptune's atmosphere since Voyager has been our increasing appreciation of just how active and variable that atmosphere is, though there were indications of this activity before and during Voyager (Joyce et al. 1977, Cruikshank 1985, Smith et al. 1989, Hammel et al. 1992, Ingersoll et al. 1995). During the Hubble era (which is now merging into the Adaptive Optics era), we have seen Neptune completely change character two or three times. The Voyager Great Dark Spot disappeared (Hammel et al. 1995), to be replaced by one or two northern hemisphere Great Dark Spots (Hammel et al. 1995, Hammel and Lockwood 1997, Sromovsky et al. 2001a), at least one of which has also subsequently disappeared (Sromovsky et al. 2001b). In the southern hemisphere as a whole, the Voyager encounter period now appears to have been rather quiescent. The latitudes between 45° and 55°S, which were featureless in 1989 except for a couple of discrete spots (Dark Spot 2 and Scooter) have erupted into nearly continuous bright features (Sromovsky et al. 2001b, Rages et al. 2001). Northern hemisphere cirrus-like features have come and gone, and the intermittent bright South Polar Feature at 70°S continues to form and dissipate within 1-2 Neptunian days while remaining fixed in latitude for more than a decade (Rages et al. 2001). What powers the winds, and why are the winds and thermal structure similar to those of Uranus (Figure 1), though the internal heat sources differ? How deep does the zonal structure go?

NEED: visible imaging and thermal mapping at many phase angles down to 10 km; occultations of radio telemetry signals to probe atmosphere down to ~2 bar.

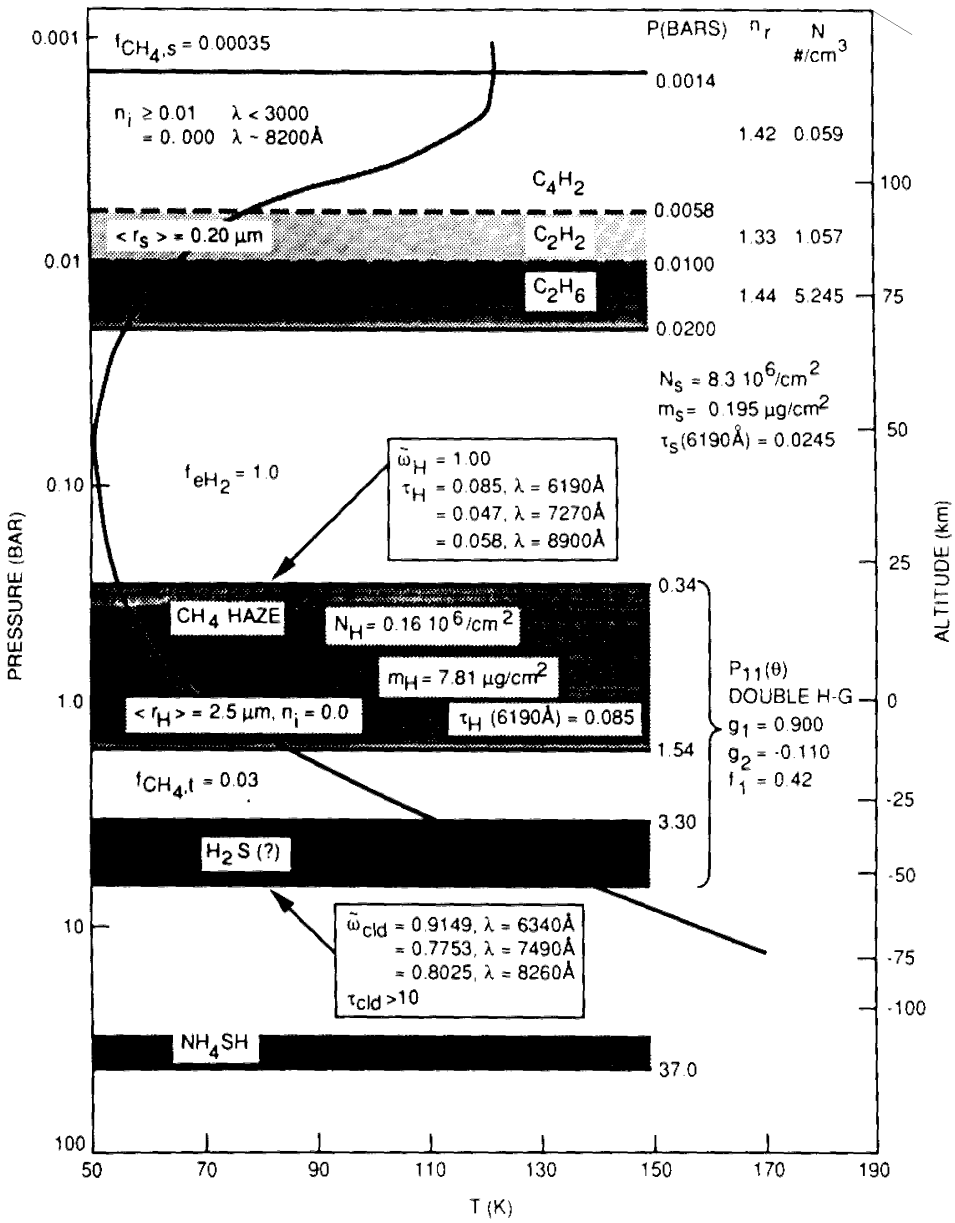

Figure 2. Neptune's vertical aerosol distribution. From Baines et al. (1995).

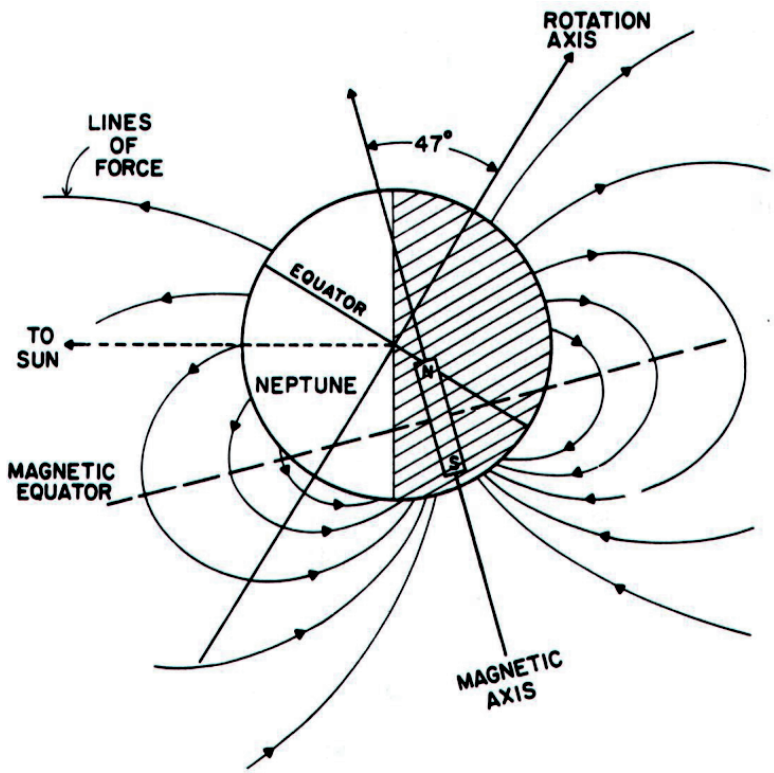

Figure 3. Neptune's magnetic field: an off-set tilted dipole. From Ness et al. (1989).

Atmospheric composition: Our understanding of Neptune's atmospheric composition (Figure 2) is still largely derived from Voyager (Bishop et al. 1995, Baines et al. 1995, Gautier et al. 1995). The atmosphere is mostly hydrogen with an ortho-para ratio near the thermal equilibrium value, and a mole fraction of 0.190-0.032 helium (Conrath et al. 1991, Gautier et al. 1995). Methane is also present in significant amounts, with a mixing ratio of 0.02-0.03 in the troposphere (Baines and Smith 1990, Lindal 1992) and 10^{-4} to 10^{-3} in the stratosphere (Orton et al. 1992, Baines and Hammel 1994). Figure 15 of Baines et al. (1995) gives the nominal atmospheric aerosol structure, a hydrocarbon haze layer at a few tens of mbar in the stratosphere, the methane cloud with optical depth of order unity and a base near 1.5 bars, and an optically thick cloud (most likely hydrogen sulfide) with a top at 3.5-4.5 bars. What is the composition of discrete features (bright and dark), and of the atmosphere as a function of altitude?

NEED: UV occultations to measure density, scale height, temperature and composition; compositional mapping at near-IR wavelengths.

Planetary interior and magnetic field environs: Neptune's field (Figure 3), like that of Uranus, is highly tilted and offset from the planet's center (Ness et al. 1989, 1995). Outside several planetary radii, Neptune's magnetic field can be

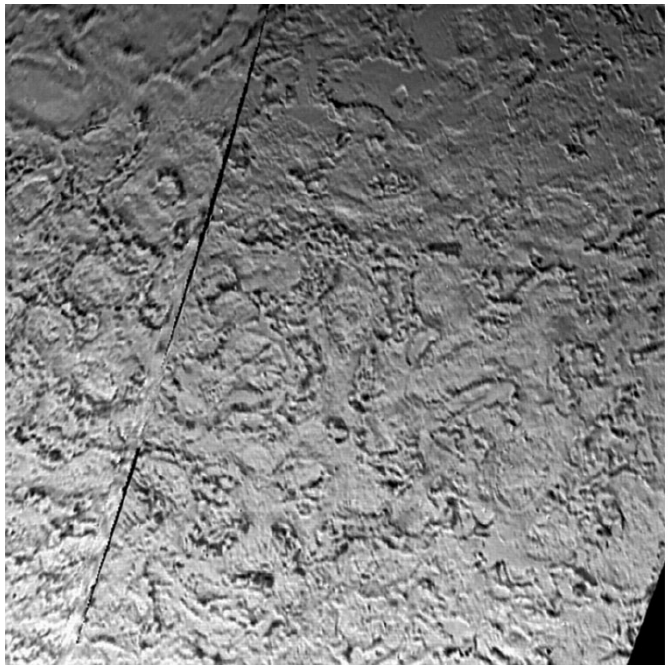

Figure 4. Triton's cantaloupe terrain. Image by P. Schenk.

represented by a dipole moment offset by at least 0.55 radii (about 8,500 miles) from the physical center of Neptune and tilted by 47 degrees with respect to the spin axis of the planet. The field strength at the surface varies from a maximum of more than 1 gauss in the southern hemisphere to a minimum of less than 0.1 gauss in the northern. (Earth's equatorial magnetic field at the surface is 0.32 gauss.) Because of its unusual orientation and the tilt of the planet's rotation axis, Neptune's magnetic field goes through dramatic changes as the planet rotates in the solar wind. For example, at the time of the Voyager 2 encounter Neptune's spin axis tipped directly away from the sun 25 degrees from ecliptic north and Neptune's equatorial plane was inclined some 29 degrees to its orbital plane. The combination of the spin axis orientation and the large tilt angle of the magnetic dipole moment caused the angle between the magnetic axis and solar wind flow to vary from 20 degrees ("Earth-like" magnetosphere) to 114 degrees ("pole-on" magnetosphere) and back every planetary rotation of 16.11 hours during the Voyager flyby. Why are the magnetic fields much more asymmetric in ice giants than in gas giants?

NEED: measurements of magnetic field and magnetospheric particles at a variety of latitudes and longitudes.

1.2. Triton

Short of exploring Pluto, exploring Triton may provide our best opportunity to examine the surface and atmosphere of a Kuiper Belt Object analog. Furthermore, some aspects of its terrain suggest that Triton may be "a cousin to Europa in unexpected ways" (Schenk 1999).

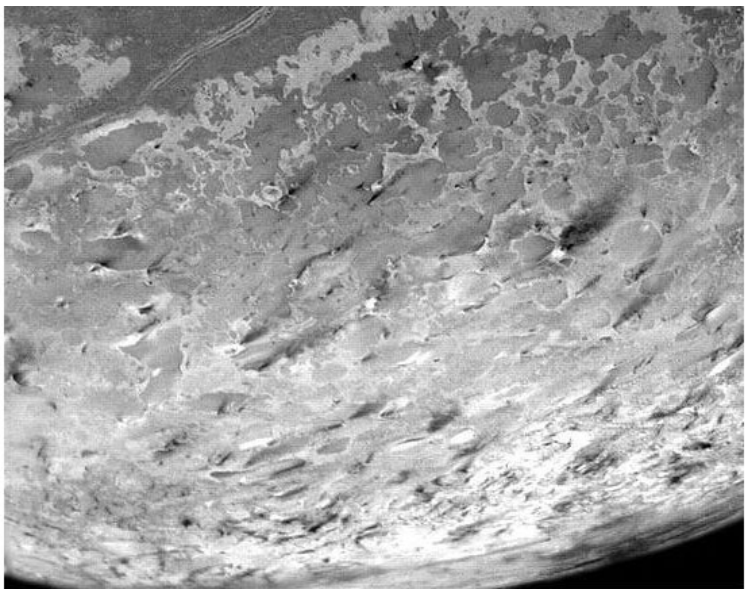

Figure 5. Wind streaks on Triton southern hemisphere. Voyager revealed the source of these dark streaks to be active cryovolcanism ("geysers"). Courtesy, NASA.

Surface geology: Triton's surface (e.g., Smith et al. 1989, McEwen 1990, Stern and McKinnon 1999) is widely thought to be younger, and more active, than almost any other planetary satellite. Croft (1990) and subsequently others (e.g., Schenk 1999) have provided overviews of the varied geology, but a key note is that less than half of Triton's surface was mapped by Voyager. What secrets does this "Triton Incognita" hold? Of the known terrain, the weirdest terrain on Triton may be the so-called cantaloupe terrain (Figure 4), characterized by closed topographic "cells" 30-40 km across. These cells may be formed by diapirs (Schenk and Jackson 1993), blobs of material that rise from depth and penetrate through a surface layer. This suggests that Triton's crust is layered.

The southern hemisphere consists of at least two distinct units: spotted and ridged terrains. The spotted terrain (Figure 5) consists of large irregular regions and is also the site of "wind streaks" and plumes (see next section). These terrains show craters and cross-cutting linear features, suggesting that they do not constitute a seasonally-deposited "polar cap" (Schenk and Moore 1993).

Stratigraphic mapping suggests that cantaloupe terrain may be the oldest unit on Triton. However, recent cratercounts (Schenk 1999) reveal unambiguously that there are no fresh impact craters larger than 4 km on cantaloupe terrain or within the transition zone between cantaloupe and volcanic terrains (which corresponds to Triton's leading-trailing hemisphere boundary). The absence of any significant impactor flux from the Kuiper Belt suggests that the cratering record on Triton cannot be used to characterize the Kuiper Belt number density. It also suggests that Triton's surface age is extremely young, perhaps effectively zero, and may well prove to be younger than Europa's! This

lends support to ideas that Triton's plumes may be related to ongoing geologic, thermal, and/or seasonal activity (next section).

Is there evidence for "recent" solid-state convective activity in an icy mantle? How does composition vary between/within surface features? What causes geologic structures on Triton's surface? Has the plume distribution changed since Voyager? Have atmospheric changes modified the surface?

NEED: UV to near-IR global imaging (< 100 m); high-resolution imaging (10-30 m) of selected locales; thermal (50 and 100 μm) mapping; global 1-km imaging spectroscopy at 1-5 μm with $\lambda/\Delta\lambda = 300$.

Atmosphere-surface interactions: The atmosphere of Triton, like that of Mars and Pluto, is in vapor-pressure equilibrium with the frost on its surface. Triton's icy surface is thought to contain the volatile frosts N_2, CO, and CH_4, as well as less volatile CO_2, coloring agents, and absorbers (see Brown and Cruikshank 1997). Changes in Triton's subsolar latitude (and the resulting changes in the insolation patterns) are predicted to lead to changes in the surface pressure of factors of 10 or more because of the exponentially sensitive temperature dependence of the volatility of the frosts (e.g., Trafton 1984, Spencer 1990, Spencer and Moore 1992; see Yelle et al. 1995 for a review). The seasonal change may be driving the sublimation of ices into the atmosphere, resulting in observable (perhaps dramatic) changes in Triton's atmospheric structure, photometric properties, and surface composition and microphysical structure, including widescale frost migration. Both ground-based and Hubble Space Telescope (HST) data indicate that Triton appears to have begun its long-awaited epoch of global seasonal change.

Occultations from 1995 to 1998 show Triton's pressure at 50 km altitude increased by 40% between mid-1995 and late-1997 (Elliot et al. 1998, 2000a, 2000b). Visible photometry and spectroscopy show changes in Triton's visible colors that last roughly one year (Buratti et al. 1999). Ultraviolet spectra obtained with the HST Space Telescope Imaging Spectrograph show that Triton's albedo and spectral slope in the UV appears extremely variable longward of 2400Å (Young and Stern 2001). Finally, near-infrared spectra (1.4 to 2.5 μm) show pronounced changes in the strength of CH_4 absorption features from 1980 to 1992, but little change between 1995 and 1998 (Brown et al. 1995, Hilbert et al. 1998).

It is fascinating to speculate about how these effects are changing the surface appearance, and about whether they are related to the active cryovolcanism detected on Triton by Voyager (Figure 5). However, Triton's size and distance preclude little more than speculation. A spacecraft to the Neptune system is required to understand the details of the surface-atmosphere interaction.

What is Triton's atmospheric composition and structure? How has it changed since Voyager? Can interactions with specific surface regions be tied to seasonal change?

NEED: radio occultations for atmospheric size/structure; high phase and high-resolution (100-300 m) limb imaging for hazes/plumes; UV occultations (density, scale height, temperature, composition); atmospheric sampling (fly-through); global mapping of surficial units.

1.3. Rings and small satellites

Rings are addressed more fully by Gordon et al. (this volume). We reiterate here a few of their points that pertain to the Neptune ring system. Voyager images revealed the complexity and variety of structure in the various ring systems. The processes that influence planetary ring structure can influence ring properties on timescales that are short compared to the age of the solar system (such processes include global angular momentum transfer, darkening caused by bombardment of rings by interplanetary projectiles, gas drag, and depletion by transfer of tiny charged grains from rings to their planet). There are uncertainties in the parameters of all these processes, but they nevertheless cause us to wonder about the origin of all four ring systems. Are they as old as the planets and their retinues of moons, or are they geologically recent and transient features of the planetary landscape?

Recent studies have identified complex gravitational interactions between the rings and their retinues of attendant satellites. The study of planetary ring dynamics has been instrumental in developing our understanding of the processes at work in the nebula during the formation of the solar system. In particular, the interactions between embedded objects and disks (spiral wave generation, angular momentum transport, truncation of disks) has been illuminated through our study of rings. Thus studies of planetary rings have been fundamental in improving our understanding of nebular dynamics and extrasolar planets.

The composition of planetary rings remains a major unknown, beyond some zero-order understanding. Saturn's rings are dominated by water ice, but their pinkish color - not dissimilar from Triton at visual wavelengths - calls for at least one important secondary component. The composition of the rings of Jupiter and Uranus is unknown: the Uranian rings are nearly, but not entirely, colorless; the Jovian ring shares the reddish color of Amalthea. Neptune's rings are fairly dark, but nothing is known about their color.

The next most interesting ring system, after Saturn, is probably that of Neptune (Figure 6). It has the additional scientific interest of being the most remote in the solar system, and the closest to the Kuiper Belt. There is a massive inner ringmoon belt with probably many smaller moons Voyager couldn't find. There are diffuse dusty rings. This is the only ring system known to possess relatively stable arcs, although the proposed confinement mechanism has recently come into question as result of recent HST observations of the clumps. The vertical and radial structure of the Neptunian rings remain unresolved. We are completely ignorant of the ring and ringmoon composition or how it varies with location, except that the material seems to be dark. We are likely always to remain ignorant if we have to rely on Earth-based observations alone.

New ground-based observations may provide more insights, but ground-based observations of the Neptunian rings have serious limitations. It is best to view dusty rings in forward-scattered light, which places the rings between the observer and the Sun. This requires a spacecraft beyond Neptune.

Is a resonant model for arc stability correct? If not, how do arcs remain stable? Do Neptune's inner satellites show the effect of extreme tidal stress? Are they a "major ring system waiting to happen"? Are the ring arcs indeed trapped or are they evolving? Are there "rubble belts" containing large boulders as well as dust? Are they the results of disruption of moons? How long ago?

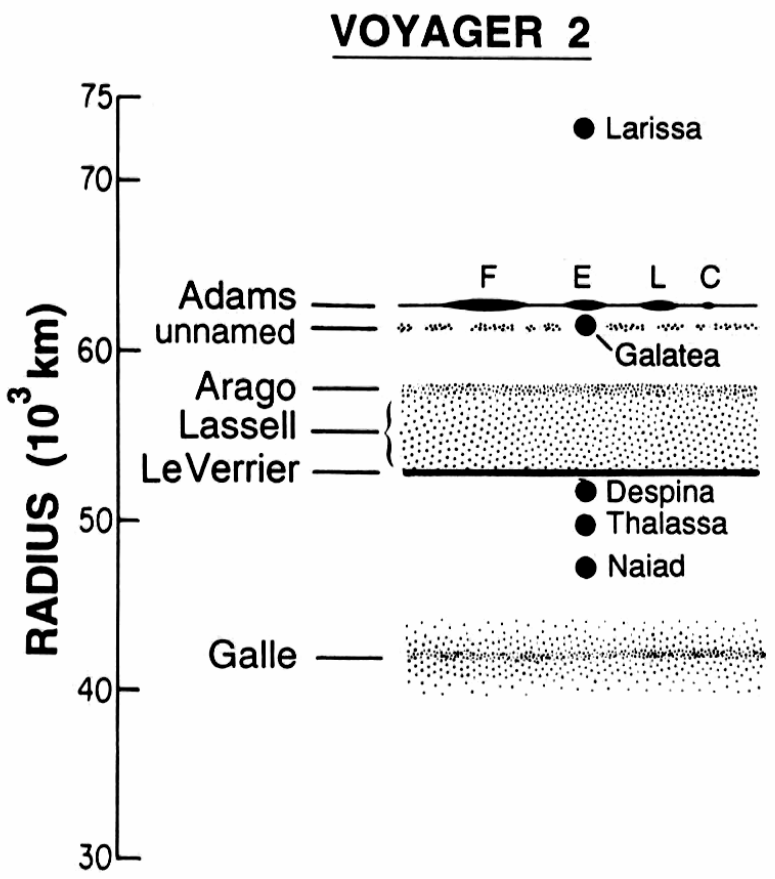

Figure 6. Diagram of Neptune's rings and satellites within the ring region. The arcs are labeled C for Courage, F for Fraternité, E for Egalité, and L for Liberté. From Porco et al. (1995).

What is the meteoritic in fall rate and composition? Voyager data contains hints of other narrow, kinky ringlets in a few as-yet unstudied images. Are they real?

NEED: low-phase 100-m scale imaging of arcs to find embedded bodies; high-phase 1-km scale imaging to detect new rings/arcs and to characterize ring/arc morphology; spectroscopic capability to determine composition.

2. Key Science Questions

The science questions naturally drive measurement objectives and, in turn, instrumentation requirements.

2.1. Neptune

- What is the three-dimensional atmospheric circulation pattern as a function of depth?

- What is the composition of deep atmosphere/interior, including the H/He, isotopic compositions, etc.?
- How does the atmosphere vary with time at smaller scales (indicated by HST-based observations for large-scale changes)?
- What are the atmospheric convection patterns and, if present, zonal circulation patterns at depth in thermal emission?
- What is the aerosol composition and particle size in the stratosphere and upper troposphere?
- What are the populations and energies of magnetospheric constituents, which are needed to understand the energy inputs to both the upper atmosphere of Neptune and the surface/atmosphere of Triton?
- What is the three-dimensional compositional structure of the atmosphere, including the upper atmosphere where aerosols are likely produced?
- What are the higher moments of the magnetic field?
- What are the higher moments of the gravity field, to determine internal mass distribution?
- What is Neptune's temperature field; how does it affect Neptune's internal heat flux?

Measurement Objectives

- Thermal mapping of the entire planet at various phase angles.
- Compositional mapping of the entire planet.
- Repeated, simultaneous narrow- and wide-angle imaging to capture atmospheric motions and to measure winds. Narrow-angle imaging scales can be 10 km.
- Imaging of limb at high phase to detect hazes.
- UV-to-IR spectral mapping and broad phase angle coverage of the atmosphere.
- Measurement of the magnetic field and magnetospheric particles at a variety of latitudes and longitudes in the rotating (magnetic) coordinate system.
- Multiple occultations of radio telemetry signals for atmosphere to 2-bar level.
- Multiple UV (stellar or solar) occultations of Neptune's atmosphere to determine density, scale height, temperature and composition.

2.2. Triton

- What are the physical properties and structure of Triton's atmosphere (temperature, pressure, scale height), including any variation with latitude?
- What is the composition of the atmosphere, including local variations arising from erupting geysers, and the abundance and distribution of aerosols?
- What is the global distribution of volatiles, including the presence of a north polar cap?
- What are the relevant surface geologic processes, including tectonic activity, volcanic/geyser activity, glacial activity, subsidence, processes of erosion and degradation, and processes affecting crater morphology (mass wasting, relaxation)?
- What is Triton's internal structure and what is the magnitude of tidal distortion?
- Have there been changes in orbital eccentricity?
- Does Triton have an induced or intrinsic magnetic field?

Measurement Objectives

- Map surface compositions, searching for correlations between particular geological and compositional units.
- Map surface temperatures to identify the sources of volatiles in the atmosphere.
- Global imaging at resolutions of 100-m from UV to near IR, especially the polar regions. (Dark side may be visible in Neptune-shine.)
- Very high resolution imaging (tens of meters/pixel) of specific locations at different latitudes, including the south polar cap region.
- Global-imaging spectroscopy from 1 to 5 μm at resolutions of 1 km, with spectral resolution of $\lambda/\Delta\lambda = 300$ in the 1-5 μm range.
- Multiple occultations of radio telemetry signals for atmospheric structure.
- Multiple UV (stellar or solar) occultations of Triton's atmosphere to determine density, scale height, temperature and composition.
- Imaging of limb at high phase to detect hazes and plumes.
- Thermal mapping of Triton's surface at 50 and 100 μm.
- Direct sampling of the Triton's upper atmosphere.

2.3. Rings and small satellites:

- What are the orbital elements of the rings (particularly the ring arcs) and the inner satellites, and do they exhibit unexpected or predicted changes over time?

- What are the details of the interactions between rings and satellites, and are there new satellites and new rings that cannot be detected from ground-based observations or HST/NICMOS?

- What are the morphologies of the ring arcs/Adam's rings, in particular is there evidence for embedded bodies and Lagrange satellites?

- Can we characterize surface processes of ring-region satellites, e.g., through examination of crater ejecta patterns and fracture patterns (perhaps similar to those seen on Phobos and Deimos)?

- What are the compositions of the rings and, if possible (at low phase), the compositions of embedded bodies/Lagrangian satellites?

- What are the compositions of ring-region satellites, looking for methane, water, carbon dioxide, other hydrocarbons, organics and silicates (particularly, the 0.9- and 1-μm bands of the silicates olivine and pyroxene)?

- What are the densities (masses), compositions, and gross geologic histories of the satellites Larissa, Proteus, and Nereid?

Measurement Objectives

- Imaging resolutions of at least 1-km on rings and satellites for orbital determination and monitoring and for mapping satellites.

- Low-phase high-resolution (100-m) imaging of ring arcs to search for arc-embedded bodies and for compositional determination of such bodies.

- High-phase imaging searches at 1-km scale for detection of new rings and/or arcs and for characterizing ring/arc morphology.

- Compositional determination of larger ring bodies and of both known and new satellites, with the ability to distinguish CH_4, CO_2, silicates, C-H bonds, etc.

- Multiple occultations of radio telemetry signals for ring-structure and particle-size characterization.

- Global mapping at resolutions of 100-m of Proteus and Larissa; imaging at resolutions of 100-m of Nereid, if possible.

- Composition and mass of Proteus, Larissa, and, if possible, Nereid.

- Orbital refinement of all of the small satellites.

Table 2. Neptune & Triton Missions: Architecture Trade Space

Mission Type	Science Return	Cost Class
Simple Flyby	Voyager-like; remote sensing, in-situ fields and particles	Discovery Plus?
Flyby With Probe(s)	Add in-situ atmosphere; Galileo-like, minus satellites & time variability	Double Discovery?
Multi-Element Flyby With Probe(s)	Multiple viewing aspects; more time variability	Flagship
Simple Orbiter	Remote sensing, in-situ fields and particles, interior (via field maps), time variability	Double Discovery?
Complex Orbiter With Probe(s)	Cassini-like; "Flagship science"	Flagship, ~$1B
Multi-Element Orbiter With Probe(s)	More detailed investigations in every aspect; synergistic	Large Flagship
NEP Orbiter With Probes	Triton orbiter; Ring observer; Nereid rendezvous	Large Flagship

3. Recommendations

We divide our recommendations into two categories: interplanetary spacecraft and activities that can be performed on or near Earth. Among all of the possible activities that we considered for the coming decade, our overall number one priority is for a robust program of technology development for deep space missions (Table 2), of which a Neptune System mission should be a flagship. Of almost equal importance is continued support of the Earth-based and future near-Earth observational programs for the Neptune System: planet, rings, and Triton.

3.1. Neptune System Mission

Given the advances in technology since the Voyager 2 Mission, a flyby would produce excellent scientific return. However, an orbiter could contribute signifi-

cantly enhanced science return: long-term coverage of atmospheric dynamics on Neptune, the opportunity for multiple high-resolution mapping passes for Neptune and Triton to measure small-scale and short-term changes, and coverage over a wide varieties of phase angles for multiple targets (atmospheres, surfaces, rings), to name just some of the advantages.

The overall science goals of a Neptune System Mission are to examine the composition, structure, and dynamics of Neptune's atmosphere; to map Triton's surface features, examine its geologic history, surface composition, and internal structure, and monitor its atmosphere and seasonal cycles; to probe Neptune's magnetosphere with extended temporal and spatial sampling; to study the rings, ring arcs, and shepherd satellites over at least 2 years; and to image and determine the densities of the satellites Larissa, Proteus, and Nereid (if possible).

Top Priority - Neptune system orbiter: The orbiter is the core of the mission, providing a remote sensing platform, in-situ probes of the magnetic field and environs, and primary data links. An integrated imaging package would include: visible imager, IR imaging spectrometer, and UV imaging spectrometer. Other remote sensing devices might include a thermal IR spectrometer and a microwave radiometer. Space physics detectors might include a magnetometer, an ion-and-neutral-mass spectrometer, and perhaps other instruments. Radio science instruments would also be necessary.

Multi-probes are an essential part of an investigation of Neptune's deep ($\sim$100 bar) atmospheric structure and chemistry. However, significant technology advances are required to enable high S/N transmission from depth in a cost-effective manner. An optimal probe package would include a main probe (GCMS; sensors for temperature, pressure, and acceleration; solar and IR radiometers; nephelometer) and at least three mini-probes (species-specific sniffers; temperature, pressure, and acceleration sensors) to sample diverse atmospheric regions.

A stretch goal would be a miniature surface lander to make in-situ studies of Triton's lower atmosphere and surface geology/composition.

Sample mission profiles have been discussed in depth elsewhere (Oberto 1999) but we mention two here just to give a flavor of the possibilities. These are merely illustrative, and a specific mission profile would have to be developed in the context of a more robust mission proposal. The first (Figure 7a) is a traditional ballistic trajectory, with launch in 2007 (probably unrealistic in the current fiscal climate, the next window for a Jupiter Gravity Assist is 2017 or later). Such a trajectory would have a 12-year flight time when launched from a Delta III/Star 48 (a more capable launch vehicle, e.g., an Atlas IIAS/Star48, could reduce the flight time by several years). The primary advantage of this type of trajectory is the lower cost inherent in the older technology. An alternative (Figure 7b) is based on Solar Electric Propulsion (SEP) technology, which has the advantage that the launch window is not constrained by Jupiter. The limiting factor for a launch window is the development of SEP technology. The flight times are similar (of order a decade). This particular orbit shows an Earth Gravity Assist, but others were considered which omit this.

An orbital mission sequence, like the specific flight profile, would be determined in detail at later planning stages, but an example follows for an optimal 2-4 year mission. The sequence has roughly four stages (Figure 8). The aerocap-

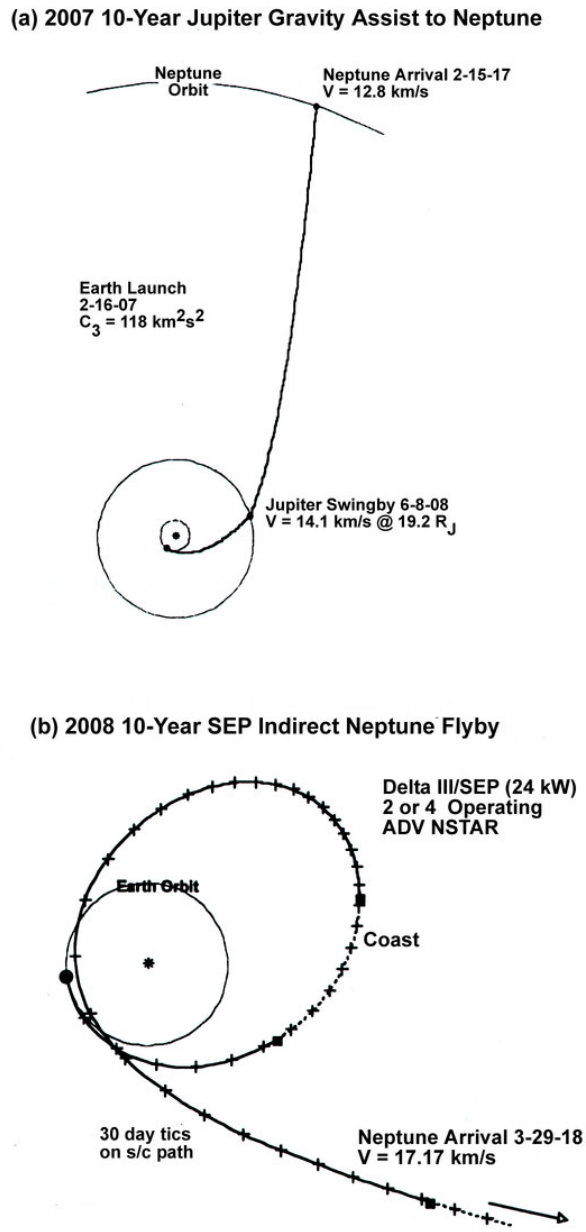

Figure 7. Sample flight profiles. (a) Traditional Jupiter gravity assist. (b) Solar Electric Propulsion. Adapted from Porco (1998).

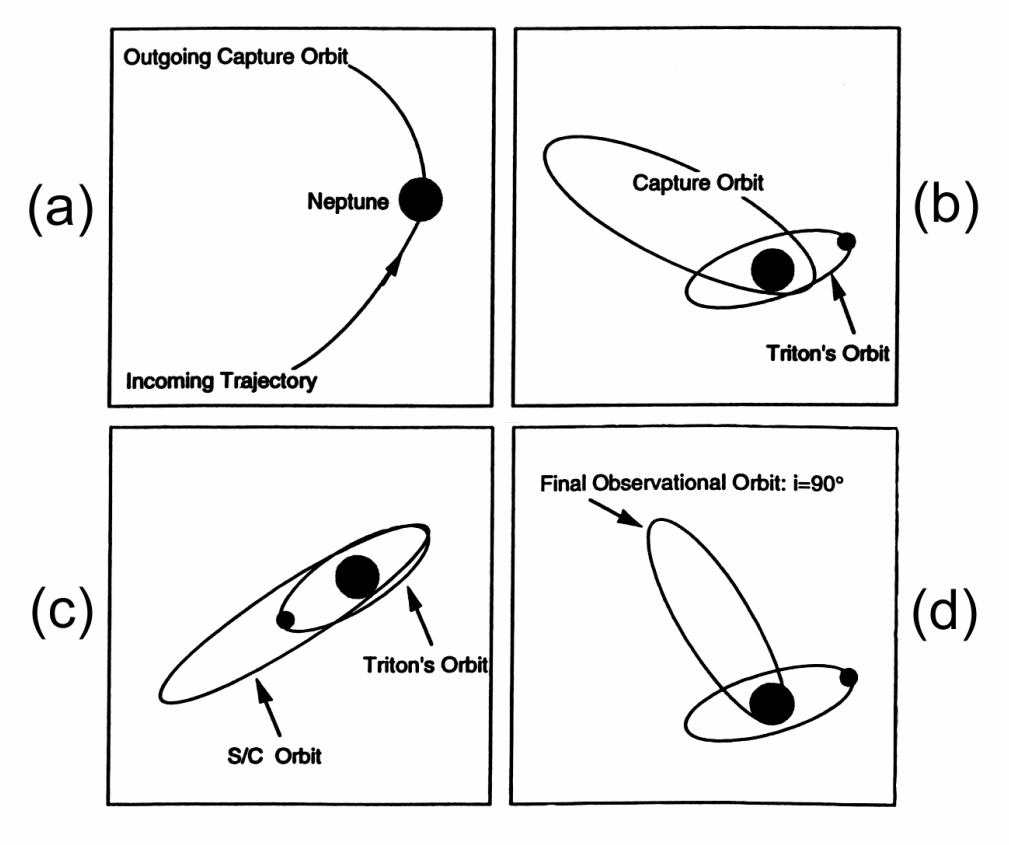

Figure 8. Sample orbital mission sequence. (a) Aerocapture. (b) Initial orbit. (c) Triton orbit. (d) Polar orbit. Adapted from Porco (1998).

ture phase (Figure 8a) employs a ballute entry into a retrograde orbit. During this phase, the spacecraft periapsis is raised above Neptune's atmosphere post-capture. In the initial orbit phase (Figure 8b), a Triton gravity assist is used to crank the spacecraft down into the Triton orbital plane. During the Triton orbit phase (Figure 8c), the spacecraft flies in a Triton coplanar orbit with a 10- to 30-day period. Triton is encountered over a range of phase angles and orbital positions. There are, of course, concomitant Neptune encounters during this phase also. During the final polar orbit phase (Figure 8d), the spacecraft orbit is cranked out of the plane by 60 to 90 degrees. Observations of Neptune and the ring plane would be the focus of this phase. Again, this example is illustrative. Data collection strategy for a Neptune System Orbiter could include the following:

- Approach coverage: atmospheric monitoring of Neptune and a possible Nereid flyby (these data can be stored and sent back later).
- Capture phase: accelerometer and fields and particles data collected for later return.

- Orbital science phase: repeated flybys and observations of Neptune, Triton, the rings, and, possibly, Proteus and Larissa; fields and particles measurements.

  This phase should last at least 2 years (3 years desired) in order to monitor changes on Triton and within the atmosphere and magnetosphere of Neptune. During this phase, the following geometries are required:

  - Closest-approach flybys of Triton at altitudes of 1000 km.
  - Closest-approach flybys of Triton at different phases in its orbit (i.e., different longitudes) and at different latitudes, including both poles.
  - Very-high-phase (>165°) viewing of Triton and the rings.
  - Closest-approach distances to the innermost satellites of ∼100,000 km at various phases in their orbits.
  - Very-close-approach, low-phase encounters with the ring arcs at ∼10,000 km.
  - Closest-approach flybys of Neptune at a variety of latitudes.
  - Repeated low-phase and contiguous Neptune observing from distances of 38 Neptune radii (∼940,000 km).

Recent studies indicate a Neptune System mission is feasible given innovative technologies (Porco 1998): high-power lightweight SEP and solar sails, qualified aeroshells, aerocapture, autonomous spacecraft communications, advances in miniaturization, lightweight power generation systems, temperature-tolerant electronics (∼50 K), and lightweight structures. These technology drivers are required for many outer planet missions. Their solutions will be broadly applicable.

High Priority - Neptune system flyby: An orbiter is strongly preferred for reasons outlined above, but a flyby would produce excellent scientific return. Given the cost constraints of the current political situation, a flyby merits discussion.

The main spacecraft would carry a remote sensing platform, in-situ probes of the magnetic field and environs, and primary data links. An integrated imaging package would include: visible imager, IR imaging spectrometer, and UV imaging spectrometer. Other remote sensing devices might include a thermal IR spectrometer and a microwave radiometer. Space physics detectors might include a magnetometer, an ion-and-neutral-mass spectrometer, and perhaps other instruments. Radio science instruments would also be necessary.

Multi-probes should still be considered for a flyby mission, and can be an essential part of an investigation of Neptune's deep (∼100 bar) atmospheric structure and chemistry. However, significant technology advances would be required to enable high S/N transmission from depth in a cost-effective manner. An optimal probe package would include a main probe (GCMS; sensors for temperature, pressure, and acceleration; solar and IR radiometers; nephelometer) and at least three mini-probes (species-specific sniffers; temperature, pressure, and acceleration sensors) to sample diverse atmospheric regions.

Data collection strategy for a Neptune System Flyby could include the following:

- Approach coverage: atmospheric monitoring of Neptune and a possible Nereid flyby.
- Closest-approach flyby of Triton at altitudes of 1000 km.
- Very-high-phase (>165°) viewing of Triton and the rings.
- Closest-approach distances to the innermost satellites of ~100,000 km at various phases in their orbits.
- Low-phase and contiguous Neptune observing from distances of 38 Neptune radii (~940,000 km).

3.2. Earth-based and Near-Earth Activities

Remarkable advances have been made in understanding the Neptune System from Earth-based observations, and given the rate of technological advancement, much more remains to be discovered this way. However, the inherent challenges in studying this distant planetary system are many (e.g., Neptune's small apparent disk - only 2.3 arcseconds, and even worse for Triton). Future requirements include: access to large telescopes; ensuring that future telescopes have the capability to track moving targets and have relevant filter selections; continued access to existing planetary telescopes; and adequate funding for observations and analyses.

Top Priority:

- Moving target capability on future space-based telescopes, e.g., NGST.
- Access to existing and future large telescopes for planetary system observations, e.g., IRTF and NGST.

High Priority:

- Long-term observing campaign for the atmosphere of Neptune.
- Long-term observing campaign for the reflectivity of Triton.
- Laboratory experiments at temperatures and pressures relevant to the Neptune system.

Priority:

- Long-term observing campaign for the rings of Neptune.
- Periodic astrometric observations of Neptune's inner satellites.
- Improvement in models and simulations pertinent to issues in the Neptune planetary system.

3.3. Education and public outreach

The Neptune System offers a wide range of phenomena to capture the public interest and to use as a springboard for a range of Education and Public Outreach activities. Following after the Galileo and Cassini mission exploration of our solar system's gas giants, a focus on an "Ice Giant" system would be timely and complementary. Given Neptune's complex rings, its unusual large moon Triton, and the fact that Neptune is the "other" blue planet, a variety of activities and educational projects can be envisioned.

3.4. Data archive and access issues

Many processes within the Neptune System operate on sufficiently short timescales to permit the detection of changes on timescales ranging from days to years, and certainly from decades or tens of decades. In order to gain insights into the underlying processes, it must be possible to access and analyze historical data. Voyager spacecraft data are archived and distributed by the NASA Planetary Data System. HST data have also been archived. However, other earth-based observations are seriously underrepresented in the archival state. The volume of planetary data will increase dramatically during the coming decade. Efforts to incorporate Earth based data should continue and tools to simplify the submission of data to the NASA Planetary Data System be developed. Funding for archiving of ground-based data would also enhance the utility of the database.

4. Summary

We are only beginning to realize and appreciate the subtle (and perhaps not so subtle) dynamics and temporal variability taking place in the Neptune system. From the planet's disappearing dark spots, to the evolving thin atmosphere of Triton, to the clumpy ring system, to the unusual magnetic field, this system provides a cornucopia of planetary system phenomena. The anticipated science return of a Neptune System Mission is limited only by the scope of the imagination of those designing the tools of exploration. The inherent difficulty of deep space exploration should not dissuade us from pursuing exploration of the Neptune System. The challenge should be met head on. The results will be worth it. Bringing our understanding of the Neptune system up to a similar level as the (Galileo) Jupiter and (expected Cassini) Saturn systems would greatly enhance the ability of the planetary community to do meaningful comparative studies. In the mean time, vigorous support of Earth-based and near-Earth facilities and programs is essential for obtaining high quality observations of this distant yet dynamic system.

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