Neptune Science with Argo – A Voyage through the Outer Solar System

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This white paper describes the Neptune science to be achieved by Argo (Neptune's rings, Triton, and the Kuiper Belt Object science objectives are described in separate white papers, authored by L. Spilker, C. Hansen and J. Stansberry, resp.)

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Argo is an innovative pragmatic concept for a New Frontiers 4 mission to significantly expand our knowledge of the outer Solar System. It exploits an upcoming launch window that permits a close Triton encounter during a flyby through the Neptune system, and then continues on to a *scientifically-selected* Kuiper Belt Object. The mission will yield significant advances in our understanding of evolutionary processes of small bodies in the outer Solar System, in addition to providing an opportunity for historic advances in ice-giant system science. By carefully focusing scientific goals and optimizing the payload, Argo can provide paradigm-shifting science within the New Frontiers cost envelope. Given the challenges of distance and time for deep outer Solar System missions and the required scientific observations, Argo is the minimum-mission possibility. The combination of all these factors makes this mission well suited to be one of the top-ranked New Frontiers mission in the next planetary decadal survey.

I. Introduction

Beginning with the first discovery of the Kuiper Belt Objects a quarter century ago, our understanding of the outer Solar System has undergone revolutionary changes. More recently – and with more import – is the realization from Solar-System-evolution studies that the locations of the outer planets have evolved significantly since their original formation. There is mounting evidence that Neptune, in particular, formed far closer to the Sun than its current remote location.

The Nice model, for example, posits that for the first several hundred million years after the formation of the planets, the outer Solar System was much more compact, with Neptune well inside 20 AU (Tsiganis et al. 2005, Morbidelli et al. 2005). Evolution of the planets' orbits eventually led to Saturn and Jupiter crossing their mutual 2:1 mean motion resonance. The resulting perturbation to Saturn's eccentricity strongly perturbed the orbits of Uranus and Neptune, leading to the current configuration of giant planets. In many N-body simulations of this evolution, Neptune was the inner ice giant prior to the resonance crossing: it may have formed within 15 AU of the Sun, only a few AU exterior to the primordial Saturn. The capture of Triton by Neptune may have occurred during this planetary reshuffling, as well as intense impact bombardment of any of Neptune's primordial regular satellites. Satellite disruption, as well as tidal capture and disruption of comets, should lead to significant rings around Neptune. Indeed, the *absence* of a massive ring system at Neptune coupled with the presence of one at Saturn is one of the more significant problems posed by the Nice model in terms of planetary ring formation (Charnoz et al. 2009).

In this new context, Neptune couples tightly with Saturn in the formation and evolution of the outer Solar System. With a detailed study of the Saturn system completed by Cassini, a new examination of the Neptune system is needed to answer the new questions raised by our improved understanding of the evolution of the outer Solar System and its coupling with the primordial and present-day Kuiper Belt.

Given these advances, it is frustrating that no missions to this realm of the Solar System are planned or expected for decades. Indeed, with the current notional timeline (e.g. *Science Plan for NASA's Science Mission Directorate*, 2007), our next glimpse of Neptune will not occur for at least half a century after the Voyager 2 flyby in 1989. Voyager's technology was already more than a decade old at the time of that encounter, and technological advances since the 1970s can provide significant scientific advances with "just flybys" at "old" targets as shown by the recent passages of New Horizons by Jupiter (*Science*, 318, 215-243, 2007) and of MESSENGER by Mercury (*Science*, 321, 58-94, 2008). Missions to Neptune have been stymied by a perception that an orbiter (i.e., a Galileo- or Cassini-like flagship mission) is required for major scientific progress. Yet nearly all aspects of the Neptune system that we can measure from Earth have changed dramatically since Voyager, including Neptune's atmosphere, its ring system, and the atmosphere of its large moon Triton. A spacecraft equipped with simple yet modern technology, on a flyby trajectory past Neptune, will yield significant new ice-giant-system science.

A Neptune flyby also provides a critical advantage over a Neptune orbiter: it gives us the opportunity to explore a ***scientifically-selected Kuiper Belt Object*** (*KBO) because of the trajectory's large bending angle due to massive Neptune.* This allows access to a vast cone of space, yielding numerous potential targets among the known KBO population. Observations of the characteristics of the KBOs open a window into the formation and early evolution of the Solar System.

Argo is an innovative mission concept for New Frontiers 4: it flies by Triton and Neptune, and continues on to explore a Kuiper Belt Object. A launch opportunity to the outer Solar System via Neptune opens in 2015 and *lasts through the end of 2019*, with backup options in 2020. It allows trajectories with reasonably short trip times to Neptune (8-11 years) and the Kuiper Belt (an additional 3-5 years), as well as low Triton approach speeds <17 km/sec. We envision a New Frontiers mission that employs current spacecraft technology (analogous to New Horizons); and a simple yet capable payload, also suggested by the New Horizons and/or the MESSENGER payload.

II. Neptune Science - Neptune's Atmosphere

Extrasolar planet hunting has matured to the point of not only detecting ice-giant-sized bodies around other stars, but even mapping out the spatial characteristics and physical parameters of these extrasolar planets (e.g., Harrington et al. 2006). Yet many basic aspects of our own nearby ice giants remain elusive. In Neptune's unusually dynamic atmosphere, aerosols (hazes and clouds in the troposphere and stratosphere) scatter and absorb incoming radiation, thus influencing the solar heating profile. That in turn affects the altitude and temperature of the tropopause and the meridional wind profile. Questions whose answers are within our grasp include: what are the natures and timescales of the mechanisms driving atmospheric circulation on an ice giant? By what process are the largest discrete atmospheric features formed and dissipated? How does seasonally-varying insolation affect energy balance in an ice-giant atmosphere? Put broadly, the big picture objectives of the Neptune atmospheric studies are to understand the processes that control the three-dimensional distribution of gas composition, clouds, temperatures, and winds in Neptune's atmosphere.

Neptune's Atmosphere: Key Scientific Questions and Measurement Objectives

1. How does the *atmosphere vary with time at smaller spatial scales*, as suggested by Earth-based observations of large-scale changes? A major development in our understanding of Neptune's atmosphere since Voyager has been the increasing appreciation of just how active and variable that atmosphere is (Fig. 1). In the past two decades, we have seen Neptune entirely change character more than once. A possible explanation for this episodic behavior, short compared to the seasonal timescale, was proposed by Smith and Gierasch (1995). They pointed out that in addition to the molecules that form clouds and thus influence the dynamics via latent heat release, the conversion of hydrogen from its ortho- state to its para- state also comprises a significant reservoir of energy on Neptune with profound effects on the dynamics in the observable weather layer. Not only might the conversion of hydrogen from para- to ortho- control the changing face of Neptune, but also it could modulate the observed infrared excess energy emitted by Neptune. By mapping the ortho-para fraction with height and latitude on Neptune (achieved with spectroscopy in the visible/near-IR), and comparing that to the limited observations from Voyager, we can start to gain a foothold on understanding these processes and extrapolate them to other worlds.

2. What are the *atmospheric convection patterns and, if present, zonal circulation patterns at depth* in thermal emission? How deep does Neptune's zonal structure go? Neptune's winds possess the largest range in velocity in the Solar System (Hammel et al. 1989, Smith et al. 1989, Hammel and Lockwood 1997, Sromovsky et al. 2001), yet the power available to drive the winds is 20 times less than that at Jupiter. This puzzling observation, that the winds increase as one moves away from the Sun, has not been explained. One theory (Ingersoll *et al.* 1995) is that the atmospheric turbulence is less at Neptune than at Jupiter or Saturn, because the power sources are less. Less turbulence allows the large-scale winds to coast along without dissipation of energy. The depth to which these zonal winds extend is unknown, but interior models (Hubbard et al. 1995) indicate that the winds involve only a few percent of Neptune's outermost mass.

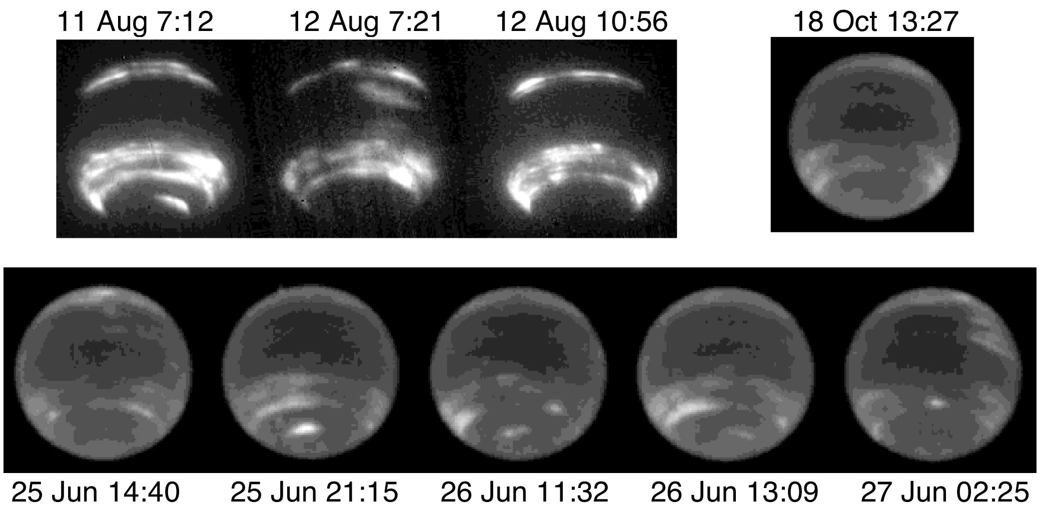

Figure 1. Neptune's clouds in 2000 (top row) and 2001 (bottom row). Top row: three Keck AO images (left) in 2000 at 2.2 mm (K') show the disappearance of a prominent South Polar Feature (SPF) in just one day (all times are UT), and an HST 619-nm image (right) from 2000 shows a faint SPF. Bottom row: HST 619-nm images from 2001 track the temporal evolution of a prominent SPF; note extended activity at the southern mid-latitudes, from Rages et al. (2002).

3. What is the *tropospheric aerosol composition and particle size* in discrete features (Great Dark Spots, bright spots), and how does it differ from the surrounding "unperturbed" atmosphere? What is the *aerosol composition and particle size in the stratosphere and upper troposphere*? Our understanding of Neptune's atmospheric composition is primarily derived from Voyager (Bishop et al. 1995, Baines et al. 1995, Gautier et al. 1995, Hammel et al. 2002). The bulk of the atmosphere is hydrogen with an *ortho-para* ratio near the thermal equilibrium value. The species CH_4, NH_3, H_2S, and H_2O, condense or chemically combine in the atmosphere of Neptune to form clouds. Baines et al. (1995; Fig. 15) gave a nominal atmospheric aerosol structure for Neptune: a hydrocarbon haze layer at a few tens of mbar in the stratosphere, a methane cloud with optical depth of order unity and a base near 1.5 bars, and an optically thick cloud (most likely H_2S) with a top at 3.5-4.5 bars. Carbon in the form of CH_4 varies from a methane mixing ratio of 0.02-0.03 in the troposphere (Baines and Smith 1990, Lindal 1992) to 10^{-4} to 10^{-3} in the stratosphere (Orton et al. 1992, Baines and Hammel 1994). Argo will map the composition of the entire planet in UV-to-IR wavelengths with broad phase angle coverage. UV occultations will be used to determine density, scale height, temperature and composition.

4. What *powers the winds*, and why are Neptune's winds and thermal structure similar to those of Uranus, though the internal heat sources differ? Imaging at routine intervals will capture atmospheric motions and measure winds. Thermal mapping of the entire planet at a wide range of phase angles is key to energy balance models.

5. What is *Neptune's temperature field*; how does it affect Neptune's internal heat flux? The first mid-infrared images of Neptune were published by Hammel et al. (2006). Their images at 8 and 12 µm revealed that mid-IR emission emerged primarily from a bright region confined to the southern pole as well as from limb brightening, especially at 12 µm. Orton et al. (2007) repeated the 8- and 12-µm images, and also obtained 18-µm images. This data, with a longer temporal baseline, clearly showed longitudinal variations in the polar region.

6. What is the *interior structure* of Neptune? Neptune's interior appears to basically follow the pressure-density relation for H_2O, although this "ice"-rich central region is overlain by an H_2-He envelope that does not exceed ~3000 km in thickness (Hubbard et al. 1995).

Neptune's Magnetosphere

Neptune's magnetic dipole (Fig. 2), like that of Uranus, is highly tilted and offset from the planet's center (Ness et al. 1989, Ness, 1994). Connerney et al. (1991) and more recently Stanley and Bloxham (2004) have attributed the large tilt and strong quadrupole moment to the thin shell structure and relatively poor electrical conductivity of the ice mantle where the magnetic field is thought to be generated.

Because of its unusual orientation and tilt, Neptune's magnetospheric field goes through dramatic changes as the planet rotates in the solar wind (see Figure 2, right). For example, during the Voyager 2 encounter Neptune's spin axis tipped directly away from the sun ~25° from ecliptic north and Neptune's equatorial plane was inclined some 29° 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° ("Earth-like" magnetosphere) to ~114° ("pole-on" magnetosphere) and back every planetary rotation of 16.11 hours during the Voyager flyby. This variation allows one to study the magnetospheric response to solar wind input on time scales of hours. Such information reveals how magnetospheres work, and can not be obtained by studying Earth, Jupiter or Saturn alone.

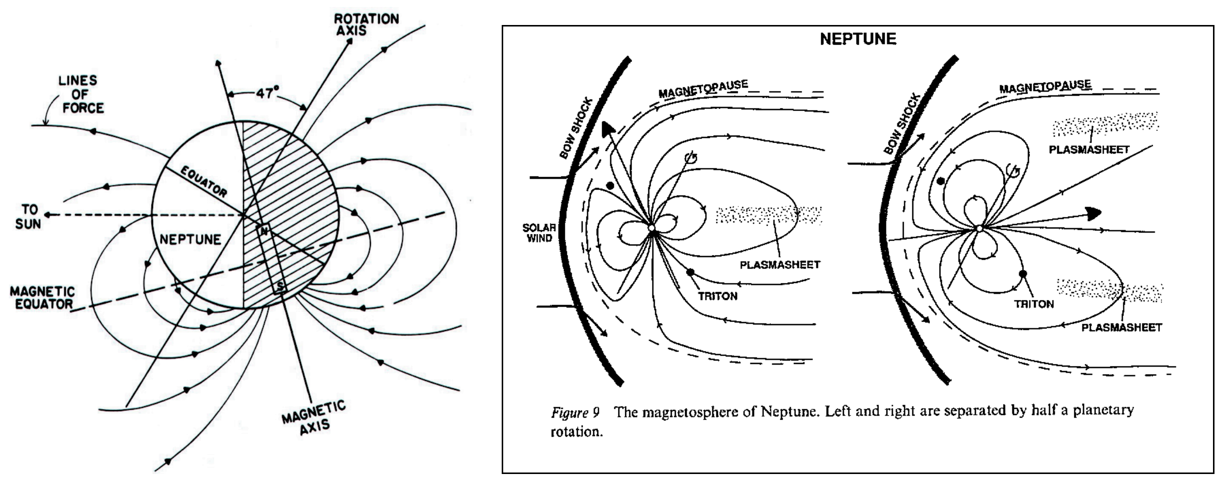

Figure 2. Neptune's magnetic field. Left: In 1989, Voyager 2 revealed Neptune's magnetic field to be off-set highly-tilted dipole (from Ness et al. 1994). Right: Changes in the configuration of Neptune's magnetosphere over a Neptunian day (figure from Bagenal 1992).

The plasma in Neptune's magnetosphere is thought to be derived mainly from Triton (Richardson et al. 1991). The N^+ escapes directly from the ionosphere of Triton into Neptune's magnetosphere, and H^+ is derived from a neutral H torus emanating from Triton. Sandel et al.

(1990) found an unusual distribution of UV emission associated with particle precipitation into Neptune's atmosphere. Paranicas and Cheng (1994), suggested that some of the non-polar distribution would be due to the unusual footpoints of magnetic drift shells in the octupole magnetic field model (Connerney et al. 1991). A strong confinement of the radiation belts by the minimum L shell of Triton was observed (Mauk et al. 1995); none of these features have been satisfactorily explained.

Magnetic Field and Magnetosphere: Key Questions and Measurement Objectives

1. What is the *generation mechanism of Neptune's magnetic field* in the low-conductivity, thin-shell-convecting interior of Neptune? Argo will measure the field over a trajectory different from that of Voyager 2 to improve our knowledge of quadrupolar and octupolar terms of Neptunian magnetic field. Voyager 2 was at a latitude of ~75º near the CA, so equatorial or south polar trajectories are prefered for the flyby, depending on KBO selection.

2. What is the *rotation period of the interior* of Neptune? Nominally we will measure the rotation period by fitting the magnetic field obtained over two widely separated time epochs. An upscope option is to add a plasma wave instrument to measure Neptune's Kilometric Radiation.

3. What are the *operational dynamics of a highly-tilted magnetosphere* that refills and empties over diurnal time scales? Is magnetic reconnection important for the motions of plasma? Argo will measure field and plasma parameters to understand plasma generation, convection, and diffusion processes. The UV instrument will image aurorae on Neptune and relate them to the reconnection electric field imposed by the solar wind.

4. What is the *composition of the plasma* in Neptune's magnetosphere? Composition will reveal information about the surface and atmosphere of Triton as well as possible contributions to the plasma from Neptune and the solar wind. Solar wind plasma access to the magnetosphere also reveals details of the magnetic reconnection and other processes.

5. How active is Neptune's magnetosphere? Neptune showed no evidence of magnetic-substorm activity during the Voyager epoch (Mauk et al. 1995), in spite of the rotationally modulated reconnection with the upstream IMF that must be present.

Table 1. Neptune Level 1 Science Questions to be addressed by Argo.

Neptune Level 1 Science Objectives	**Data Required**	**Instrument(s)**
1. *Investigate why atmospheric activity varies with time and explain overall energy balance; in particular role of otho-para hydrogen conversion as an energy supply*	Atmospheric movies, nearIR spectra	Visible imager, near IR spectrometer
2. What are the *atmospheric convection patterns and, if present, zonal circulation patterns at depth*?	Atmospheric movies, temperature map	Visible imager, thermal mapper
3. Determine *tropospheric aerosol composition and particle size* in discrete features and the surrounding "unperturbed" atmosphere	Global maps at all wavelengths, range of phase angles	UV and Near IR imaging spectrometers
4. Determine process that *powers the winds*	Movies and thermal map	Visible imager, thermal mapper
5. Map *Neptune's temperature field*; determine how it affects Neptune's internal heat flux	Global thermal map (poles are important)	Thermal mapper
6. Investigate the *interior structure* of Neptune	Close flyby to get gravity field	Radio science link

7. What is the *generation mechanism of Neptune's magnetic field* in the interior of Neptune?	Quadrupolar and octupolar terms of magnetic field	Magnetometer
8. Study the *operational dynamics of a highly-tilted magnetosphere*	Magnetic field and plasma flux; images of aurora	Magnetometer, plasma spectrometer, UV
4. Determine the *plasma sources* in the magnetosphere	Ion flux	Plasma spectrometer
5. Investigate the dynamics of the *high-energy particles and radiation belts* in Neptune's magnetosphere	Ion flux, auroral images	Plasma spectrometer, UV imager

III. Mission Description

Trajectories

A window of opportunity to go to Neptune in a relatively short amount of time (8 – 11 years) using gravity assists at Jupiter and Saturn exists from 2015 to 2019, with a few backup launch opportunities in 2020. These trajectories are similar to the tour flown by Voyager, featuring a flyby of Jupiter ~1.5 years after launch, and Saturn flyby ~3 years after launch. The geometry of the Neptune flyby is determined by a balance of desired Triton viewing geometry and KBO selection. Figure 3 shows an example of the type of trajectory and trip time that is available in 2019.

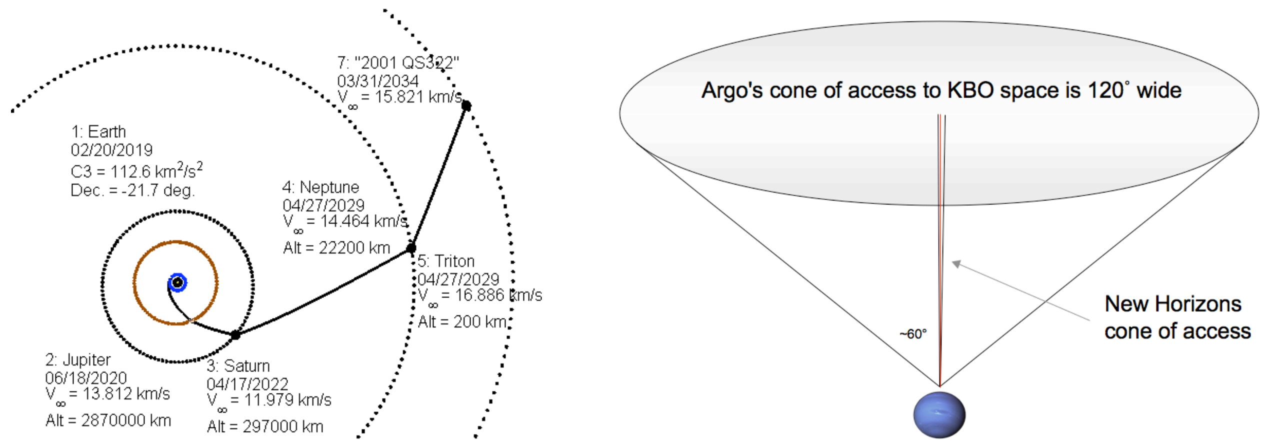

Fig. 3. A. This trajectory features a Jupiter and Saturn gravity assist that result in a flight time to Neptune of 9 years and a KBO flyby 4 years later. B. Argo access to the Kuiper Belt compared with New Horizons.

Flight System

The Argo spacecraft would be functionally similar to the New Horizons spacecraft already *en route* to Pluto. Argo will need onboard data storage to retain the copious data taken during close encounters, for subsequent relay to Earth. Also like New Horizons, the Argo spacecraft would require a radioisotope power source (RPS) for electric power.

Table 2. Strawman Payload

Instrument	**Heritage**	**Anticipated Capability**
High-Resolution	NH LORRI	A high resolution camera will provide the highest-resolution images of Triton and a KBO, discrete features in Neptune's atmosphere, and high-phase-angle

Visible Imager		observations of the rings over a wavelength range of 300 to 900 nm (the Voyager camera was only sensitive to ~ 600 nm). Includes broadband color.
Near-infrared Imager	NH Ralph	A near-IR instrument capable of mapping the distribution of surface frosts; this technology did not exist at the time of the Voyager Encounter. Distribution of CH_4, CO and CO_2 ices will address volatile transport on Triton and the KBO.
Ultraviolet Imaging Spectrograph	Reduced Cassini	The ultraviolet instrument will observe stellar and solar occultations to study Triton's and KBO's and Neptune's atmosphere and rings. FUV imaging will be used to map water distribution on the KBO and aurora on Neptune.
Thermal Imager	LRO Diviner	Multi-channel infrared filter radiometer, where each channel is defined by a linear, 21-element, thermopile detector array at the telescope focal plane, and its spectral response is defined by a focal plane bandpass filter.
Plasma Spectrometer	Messenger FIPS	Measures the flux of ions as a function of mass per charge and the flux of ions and electrons as a function of energy per charge and angle of arrival.
Magnetometer	ST5	The magnetometer will derive quadrupolar and octupolar moments of the field

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