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

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This white paper describes the Triton science to be achieved by Argo, a flyby mission to Neptune, Triton and a KBO (Neptune and the Kuiper Belt Object science objectives are described in separate white papers)

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Argo is an innovative 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). 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 Nice model satisfactorily explains many Solar System features, including evidence of a Late Heavy Bombardment (Gomes et al. 2005), the origin of the Trojan asteroids (Morbidelli et al. 2005), the current configuration of the giant planets (Tsiganis et al. 2005, Levison et al. 2008), and possibly even the origin of Saturn's rings (Charnoz et al. 2009).

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. The consequences of a Late Heavy Bombardment on Neptune's moons include alteration of the size distribution of moons through fragmentation, impact cratering, and disruption of moons to form rings. In the 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.

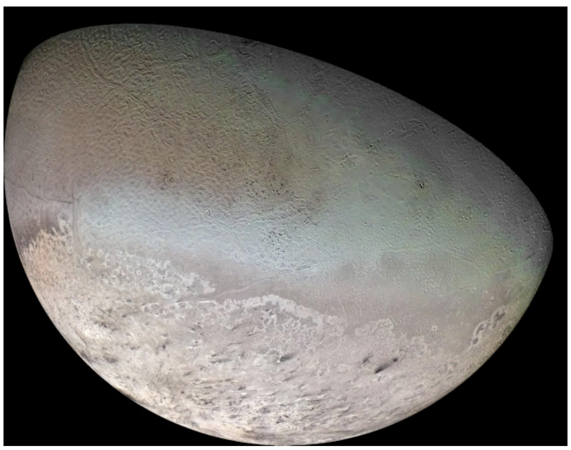
Given these advances, it is frustrating that no missions to this realm of the Solar System are expected for decades. Indeed, with the current notional timeline (e.g. *Science Plan for NASA's Science Mission Directorate*, 2007), our next glimpse of the Neptune system will not occur for at least half a 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). Nearly all aspects of the Neptune system that we can measure from Earth have changed dramatically since Voyager, including the atmosphere of its large moon Triton. Thus, a spacecraft equipped with simple yet modern technology, on a flyby trajectory past Neptune, will yield significant new science.

Argo is a pragmatic, 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 (comparable to Voyager). 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. Nuclear power is required in these far reaches of the outer solar system. Neptune's massive gravity opens an access cone of 120^0 allowing us to bend the trajectory to a *scientifically-selected* Kuiper Belt Object.

II. Triton Science

The Argo science payload and trajectory offer exceptional opportunities to increase our understanding of small primitive bodies in the outer Solar System by first executing a close flyby of Triton, followed by a flyby of an *in situ* KBO. It is widely accepted that Neptune's largest satellite Triton is a captured KBO (Triton's ~6-day orbit is retrograde and highly inclined, ~23°). Yet key questions remain about how and when it was captured. Tidal energy released as Triton's orbit was gradually circularized should have been sufficient for Triton to differentiate, but there is no measurement of its moment of inertia to be certain. Triton is now locked in a synchronous orbit with nearly the same longitude always facing Neptune (unless there is a slow nonsynchronous rotation of an ice shell over a subsurface ocean yet to be detected).

Fig. 1. The best hemispheric mosaic acquired by Voyager was of the sub-Neptune side of Triton (Smith et al. 1989). At the time of the Voyager flyby the season was late spring with a subsolar latitude of 45°S.



Voyager returned our first (and only!) close-up Triton data in August 1989. Three days out, the anti-Neptune hemisphere was imaged at a range of 0.5 million km and resolution of 60 km (Smith et al. 1989). The sunlit southern hemisphere was imaged with a resolution of 5 km. Highest resolution of ~1 km was achieved when Voyager made its closest approach, 40,000 km from Triton. Triton has a young surface with very few impact craters. Northwest of the equator, "cantaloupe terrain" crisscrossed with quasi-linear ridges is observed (Fig. 1). Northeast of the equator smooth, hummocky and knobby plains material is prevalent. The bright south polar region may show evidence of the distribution of seasonally mobile ice during the Voyager 2 flyby, and dark fans of dust were observed on the surface.

Triton's surface is partially covered with nitrogen ice, and trace constituents methane, CO, and CO_2 ice (Cruikshank and Apt 1984, Cruikshank et al. 1984, Cruikshank et al. 1991). With a surface temperature of 38 K nitrogen forms a thin atmosphere in vapor pressure equilibrium with surface ice (Conrath et al. 1989). Voyager measured an atmospheric pressure of 14 microbars (Broadfoot et al. 1989). Nitrogen frost will move around seasonally from pole to pole, in and out of the atmosphere, with a behavior similar to CO_2 on Mars (Spencer 1990, Stansberry et al. 1990, Hansen and Paige 1992).

Most surprising of all was the discovery of two plumes erupting from the surface (Soderblom et al. 1990). They were hypothesized to be solar-powered, driven by seasonal sublimation and storage of nitrogen under translucent ice, pressurized, then released (Kirk et al. 1990). The numerous dark fans on the bright surface with orientations determined by the prevailing wind were probably deposited on the surface by plumes, no longer active at the time of the Voyager snapshots. This model of solar-powered activity has flaws however, including the size of the sub-ice nitrogen reservoir required, and thus the origin of the plumes is still a mystery.

Radio science observations revealed a significant ionosphere with a well-defined peak at ~350 km altitude (Tyler et al. 1989). 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. Heavy ions, likely associated with Triton's exosphere were observed to be concentrated towards Neptune's magnetic equator (Belcher et al. 1989, Richardson et al. 1995).

The outer extent of the high-energy (> ~ 1 MeV) radiation belt particles at Neptune is set by Triton's orbit, thought to possibly "sweep up" these particles as it orbits Neptune (Stone et al. 1989). This behavior extends to lower energies, but electrons with energies of 10s of keV are present at Triton's orbit and may be the principal driver for auroral emissions seen by Voyager. Changes in the electron spectral index (~20 to 60 keV) peaks at Triton's location and is an additional signature of the significant interaction of the moon with Neptune's magnetosphere at these energies (Krimigis et al. 1989, Mauk et al. 1995).

No magnetic signature of Triton was found by Voyager due to the remoteness of the flyby. The observation of an intrinsic magnetic field of Ganymede (Kivelson et al. 2002) has also shown that magnetic dynamo activity, once thought to be the singular province of Earth and the large planets, is more ubiquitous than once thought and cannot be *a priori* ruled out for Triton.

Triton: Key Science Questions and Measurement Objectives

1. What is the *origin and history of Triton's differentiation*? What does the evolution of its interior tell us about the capture process? Does Triton have a *current or past dynamo magnetic field*? If Triton was captured very early in the history of the Solar System, aided by an extended proto-Neptunian atmosphere, then tidal evolution to a circular orbit and differentiation should have been complete in order 10^8 yrs, followed by billions of years of impact cratering. Yet the surface is lightly cratered. Was it actually captured much more recently, perhaps one body of a binary KBO (Agnor and Hamilton 2006)? Or has cryovolcanism played a major role in renewing the surface?

A close pass (~10^3 km or about a Triton radius of 1353 km (McKinnon et al. 1995)) to Triton will enable measurement of its moment of inertia to better constrain its internal differentiation. To measure the magnetic field and the induction response of the moon to the rotating field of Neptune requires a very close pass at an altitude of less than 0.5 R_{Triton}). We will measure the interaction signal in the magnetic field (Alfvén wings, plasma pick-up currents, plasma interaction currents etc.) and plasma data (flow slowing and diversion, plasma temperature changes, ring-beamed plasma distributions etc).

2. What is the *cratering record* on Triton and how does it relate to and constrain Solar System formation and early evolution scenarios? Since Triton is the only major satellite around Neptune, it probably has not been received many sesquinary craters, i.e. from ejecta from large impacts onto other satellites (Zahnle et al. 2008). Hence, Triton may provide the very best place to measure the size-frequency distribution of comet-formed impact craters, which in turn will help us to understand cratering chronology throughout the Solar System (Zahnle et al. 2003). However, if Schenk and Zahnle (2007) are correct about a strong concentration of the craters on the leading hemisphere from planetocentric cratering, then the craters may not tell us about comets. Triton has been only partially imaged, leaving us with more questions than craters.

3. How spatially homogeneous is Triton's surface, or, put differently, what *undiscovered geologic features* lie in regions that were not well-imaged by Voyager? How are *ices* partitioned across the surface? Argo will extend global coverage and maps by imaging portions of Triton that were in darkness or only imaged at low resolution by Voyager. We want to determine the surface evolution chronology, study the tectonic network, and interpret new data with the perspective of what this tells us about the capture of Triton. Although the subsolar latitude has changed, it has actually just passed through solstice at 52°S and is now on its way back toward the equator, so the subsolar latitude at the time of the Argo flyby will be ~30°S, and an entirely new swath of territory in the northern hemisphere will be illuminated.

4. How do *volatile inventories compare between Pluto, Triton, and Argo's in situ KBO*? How has *seasonal volatile migration* affected the south polar cap and atmosphere since Triton has gone from southern spring (Voyager) to summer (Argo)? How much mass has been transferred into the atmosphere and northern polar region? Changes in atmospheric pressure since the Voyager flyby have been detected in stellar occultations observed from earth

(Elliot et al 2007). Solar and stellar occultations will be observed at ultraviolet wavelengths to measure atmospheric pressure at the time of the Argo flyby. Seasonal volatile migration takes place on Pluto, which also has a nitrogen atmosphere in vapor pressure equilibrium with the surface frost (Hansen and Paige, 1996). It is reasonable to expect that other KBOs will have similar volatile climates, if they are large enough to hold onto their atmospheres gravitationally, not losing them to Jeans escape or solar wind erosion (Schaller and Brown, 2007).

5. Are Triton's *plumes* a result of solar-driven activity? Are the plumes observed by Voyager 2 still erupting, and if so, in the same places or in new areas? What do the sites and timings of occurrence tell us about the energetics, relevant processes, and the nitrogen reservoir? Similar solar-driven activity may also be occurring on Mars (Kieffer, 2000), and Triton may prove to be a wellspring of information about this poorly-understood phenomenon. Repeat coverage of the south polar region at the resolution and lighting of Voyager is likely to reveal dramatic changes, if the plumes are indeed solar-driven.

6. What can we learn about the *formation and distribution of aerosols* in Triton's atmosphere? How has the *wind regime on Triton* changed since the Voyager flyby, post-southern solstice? Spacecraft observations of the plumes, atmospheric haze, exosphere, and particle environment are the only means of addressing this question. The orientation of fans of fines on the surface compared to their direction at the time of the Voyager encounter will show changes in the wind.

7. How is the relatively *dense neutral torus* of Triton formed, and what is its relationship, if any, to active vents on Triton and/or loss processes from Triton's atmosphere?

Measurements of ions and electron fluxes as a function of energy-per-charge and composition of the ions along the trajectory of the spacecraft can be related to the neutral torus densities by modeling charge-exchange and ionization processes. Recently picked-up non-thermal distribution of ions in the exosphere and wake of Triton will provide information on the surface composition of Triton. We may be able to quantify the frequency and amplitude of ion cyclotron waves in the vicinity of Triton with an onboard magnetometer.

8. How does highly conducting Triton *interact with the corotating magnetosphere* of Neptune? Is this related to the generation and maintenance of Triton's extremely strong ionosphere, which has a peak electron density of 2–5 x10^4 cm^{-3}? We can quantify the density and temperature of the ionosphere by modeling the radio signal occultation of the earth by the ionosphere. Passage through Triton's wake will further constrain composition by measuring in situ both material coming from Triton's ionosphere and exosphere and by sampling energetic particles responsible for a significant part of the ionosphere's production and maintenance. These experiments are however subject to constraints on the trajectory that will emerge when we select the KBO.

Table 1. Triton Level 1 Science Objectives to be addressed by Argo.

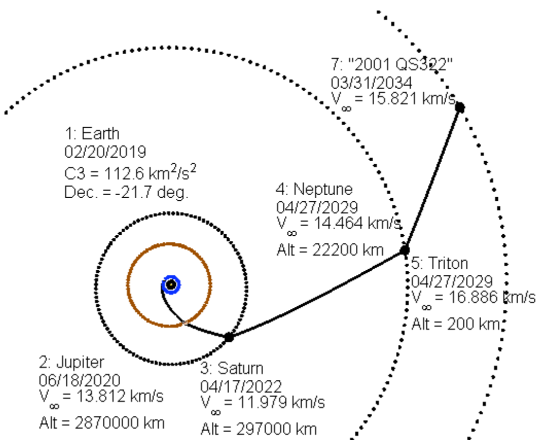
Triton Level 1 Science Objectives	Data Required	Instrument(s)
1. Investigate interior structure: Is Triton *differentiated*? Does it have an *internal magnetic field*?	Moment of inertia, existence of induced magnetic field	Radio link, magnetometer
2. Determine the *cratering record* on Triton and how it relates to and constrains Solar System formation and early evolution scenarios	Global map with better resolution and coverage than Voyager	High resolution visible imager
3. Characterize geology in regions that were not well-imaged by Voyager and map surface composition	Global visible, nearIR and uv maps	High resolution visible imager, near IR and UV spectrometers
4. Compare *volatile inventories between Pluto, Triton, and Argo's in situ KBO*. Investigate how *seasonal volatile migration* has affected the south polar cap and atmosphere.	Map surface composition, measure atmospheric pressure via occultations, map surface temperatures	Near IR and UV spectrometers; thermal mapper

5. Are Triton's *plumes* a result of solar-driven activity?	Observe plumes at same or better resolution than Voyager; look for new plumes and fans	High resolution visible imager
6. Characterize *formation and distribution of aerosols* in Triton's atmosphere	Image aerosols on limb	Visible imager w/ broadband color
7. How is the relatively *dense neutral torus* of Triton formed?	Measure ion and electron fluxes, plasma composition	Charged particle spectrometer
8. How does highly conducting Triton *interact with the corotating magnetosphere* of Neptune?	Radio occultation	USO, gimbaled high gain antenna

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 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 path from Saturn to Neptune is largely determined by the choice of the subsequent KBO. Details of the geometry of the Neptune flyby are determined by a balance of desired Triton viewing geometry and KBO selection. Figure 2 shows an example of the type of trajectory and trip time that is available in 2019.



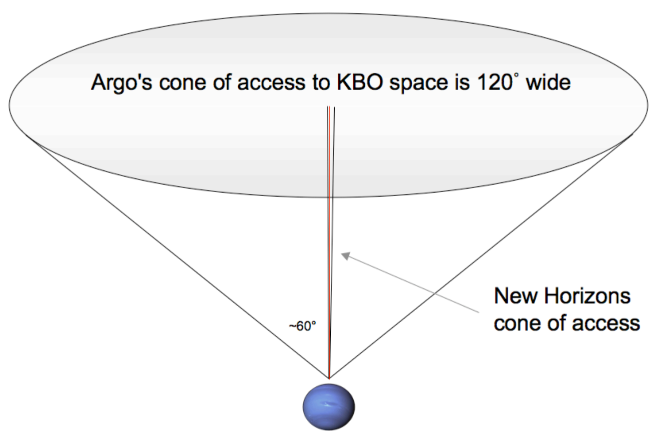


Fig. 2A. This trajectory features a Jupiter and Saturn gravity assist that result in a flight time to Neptune of 10 years and a KBO flyby 4 years later. Fig. 2B. Kuiper Belt Object access cone.

Minor tweaks to Argo's Neptune encounter trajectory can make use of Neptune's large mass to allow the post-encounter trajectory to be targeted to a *scientifically selected* KBO. The region of access includes a large number of KBOs that are already known. This set of potential targets is available on trajectories constrained to satisfy at least some of the Triton encounter science objectives discussed above. The final selection will balance KBO and Triton encounter geometry requirements.

Flight System

The Argo spacecraft would be functionally similar to the New Horizons spacecraft already *en route* to Pluto. Like New Horizons, Argo will need onboard data storage to retain the copious data taken during close encounters, for subsequent relay to Earth. The Argo spacecraft would use a radioisotope power source (RPS) for electric power. An attractive option is to decouple high-gain antenna (HGA) pointing from science-instrument pointing by articulating the HGA via a gimbal, as is currently employed on Mars orbital missions. This affords significantly greater flexibility in scheduling science-data acquisition and downlink periods, with the possibility of doing them simultaneously. For a modest 10 W of RF power out, downlink data rates of 5 to 15 kbps are available depending on HGA diameter.

Table 2. Strawman Payload

Instrument	**Heritage**	**Anticipated Capability**
High-Resolution Visible Imager	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 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, 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.
Charged Particle Spectrometer	Messenger FIPS, Cassini CAPS	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 relative to the instrument. Information on composition, density, flow velocity, and temperature of ions and electrons will be derived from the flux measurements. An energy range of a few eV to several tens of keV is desired for both ion and electron measurements.
Magnetometer	ST5	The magnetometer will look for signs of present or past dynamo magnetic field in Triton to try to infer the presence of a liquid ocean through electromagnetic induction studies that use the rotating magnetic field of Neptune as a sounding signal.

IV. Summary

Triton is one of the most dynamic icy worlds in the Solar System, comparable to yet very different than Europa and Enceladus. A mission to Triton/Neptune and beyond can be achieved within New Frontiers resources, yet the depth and breadth of science would be filled will historic "Firsts". No spacecraft will have flown by an ice giant system in two decades, whereas *every other class of object in the Solar System* has had -- or will have -- at least a flyby by 2015, if not multiple flybys and/or orbiters. For all these reasons, Argo should be considered a top candidate for the New Frontiers 4 selection.

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