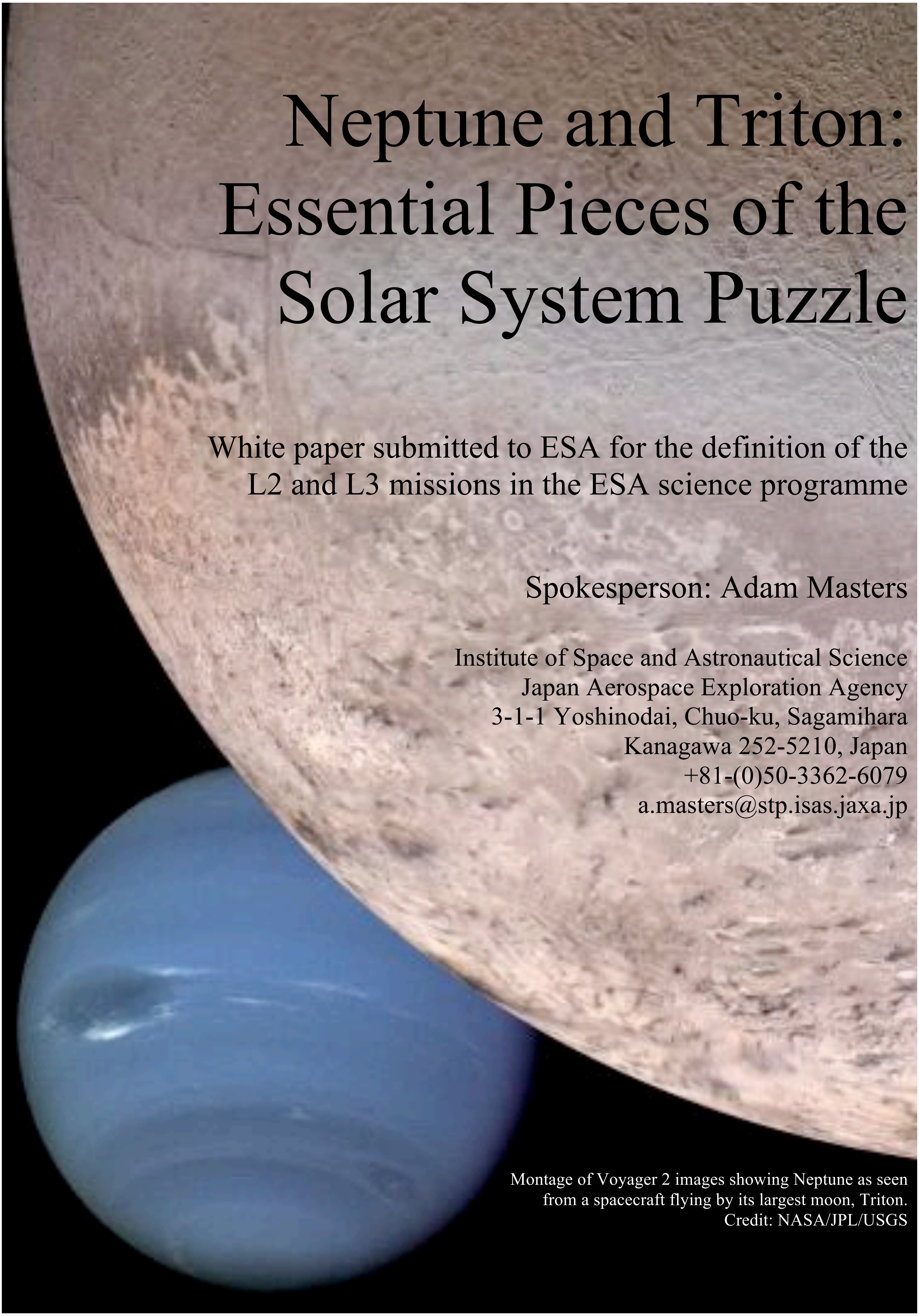

Neptune and Triton: Essential Pieces of the Solar System Puzzle

White paper submitted to ESA for the definition of the L2 and L3 missions in the ESA science programme

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Montage of Voyager 2 images showing Neptune as seen from a spacecraft flying by its largest moon, Triton. Credit: NASA/JPL/USGS

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Executive Summary

Following the focus on addressing fundamental scientific questions in the Jupiter system, the Neptune system is a strategic and high-priority target for the European planetary science community. Neptune played a unique and important role in the process of Solar System formation. Within our Solar System Neptune is most similar to the dominant class of (Neptune-sized) detected exoplanets, and Neptune's largest moon Triton is very likely a captured Kuiper Belt Object. Neptune and Triton hold the keys to paradigm-changing advances in multiple fields of planetary science: Solar System and planetary formation, exoplanetary systems, geology and geophysics, atmospheric science, magnetospheric physics, and astrobiology. An L-class Neptune orbiter mission with multiple Triton flybys would lead to major scientific advances, addressing more than half of the ESA Cosmic Vision scientific questions in a single mission.

Neptune's internal heat flux significantly exceeds solar input, producing the most meteorologically active atmosphere in the Solar System despite its great distance from the Sun. This is in stark contrast with Uranus, which has a very low internal heat flux likely due to collisional processes. Sub-Neptune-sized planets are the most numerous class of detected exoplanet, with Neptune the Solar System planet most analogous to the majority of exoplanets. Key science questions include:

- How did the Neptune system form, what role did Neptune play in the dynamics of the early Solar System, and what does this outermost planet tell us about the numerous Neptune-sized exoplanets?
- What are the relative element abundances in Neptune's interior? Is the deep interior convective?
- What powers the most meteorologically active planetary atmosphere in our Solar System?
- How can we explain the unique composition and dynamics of Neptune's rings and small moons?

Neptune's largest moon Triton is very likely a captured Kuiper Belt object, holding the answers to questions about the icy dwarf planets that formed in the outer Solar System. Furthermore, Triton is geologically active, has a tenuous nitrogen atmosphere, and is predicted to have a subsurface ocean, making it a potential habitat of considerable scientific interest. Key science questions include:

- Does Triton retain any physical memory of its origins as an icy dwarf planet?
- What is the state of Triton's interior and surface, and what is the extent of geological activity?
- What is the detailed composition of Triton's atmosphere and what drives the plumes?
- How are Triton's surface, Triton's atmosphere, and Neptune's magnetosphere coupled?
- Does Triton have a subsurface ocean? If so, what are its characteristics and is it a potential habitat?

A Neptune orbiter mission with multiple Triton flybys would address this range of major scientific questions. Enabling technologies are: extended deep space network capability, radioisotope thermoelectric power generators, and solar electric propulsion. Preliminary mission analysis suggests that the interplanetary transfer time to Neptune is 15 years (using an Ariane 5 ECA launcher, and with a Jupiter gravity assist). We present an example 2-year Neptune tour with 55 Triton flybys.

Relevant ESA Cosmic Vision scientific questions:
1. What are the conditions for planet formation and the emergence of life?
1.1 From gas and dust to stars and planets
1.2 From exoplanets to biomarkers
1.3 Life and habitability in the Solar System
2. How does the Solar System work?
2.1 From the Sun to the edge of the Solar System
2.2 The giant planets and their environments
2.3 Asteroids and other small bodies
3. What are the fundamental physical laws of the universe?
3.1 Explore the limits of contemporary physics

1. Introduction

Neptune is classified as one of the gas giant planets, along with Jupiter, Saturn, and Uranus, and is also often grouped with Uranus and referred to as an "ice giant", because these two planets are both primarily composed of "ices" (volatile elements heavier than hydrogen and helium). However, there are fundamental and important differences between the Uranus and Neptune planetary systems, which their common classification as ice giant planets should not obscure. It is the aim of this white paper to highlight the tremendous importance of the Neptune system for European planetary science, and to outline the wide range of high-priority scientific questions across multiple fields that this planetary system can provide answers to.

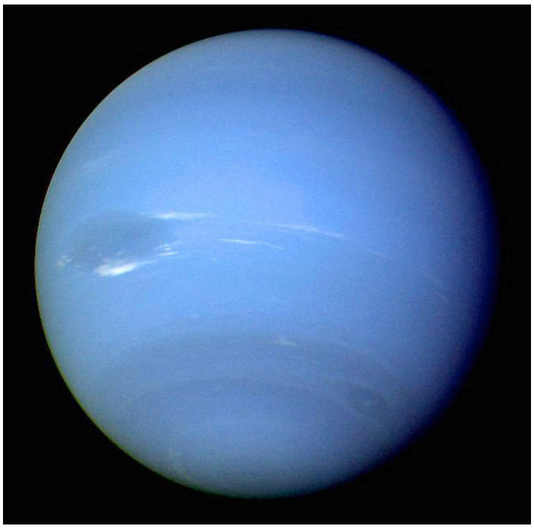

Figure 1. Neptune, captured by the Voyager 2 narrow-angle camera. Credit: NASA/JPL.

Neptune orbits the Sun at a distance ~30 times greater than the mean Sun-Earth distance (an Astronomical Unit, AU). The planetary obliquity of ~30° leads to seasons over Neptune's ~165-year orbit. A Neptune day is just over 16 hours long, and the planet is surrounded by a system of rings and icy moons (6 regular, 7 irregular). Triton, by far the largest moon, very likely formed as a dwarf planet in the Kuiper belt (like Pluto) before being captured by Neptune. This makes Triton a unique planetary satellite in the Solar System.

Voyager 2 is the only spacecraft that has encountered Neptune to date, flying by the planet on 25 August 1989 when it was summer in Neptune's southern hemisphere. Figure 1 shows Voyager 2 imaging of Neptune during approach to the planet. The combination of this brief encounter and telescope observing campaigns have shown us that Neptune has the most meteorologically active atmosphere in the Solar System, despite its distance from the Sun, and that Triton has been (and could currently be) geologically active. Neptune is barely explored when compared to other planetary systems, and never with modern spacecraft instrumentation.

A range of fundamental scientific questions concerning the Neptune planetary system are discussed in Section 2 of this white paper, with those questions concerning Triton outlined separately in Section 3. Because the theme of Neptune-Triton science is highly relevant for multiple scientific fields, both Sections 2 and 3 are divided into subsections on this basis. The important science that could be carried out by a spacecraft during an interplanetary transfer to Neptune is covered in Section 4. Finally, in Section 5 we discuss L-class Neptune orbiter mission concepts including multiple Triton flybys that would address all the major science questions. Identifying enabling technology is a priority.

2. Neptune

Relevant ESA Cosmic Vision scientific questions:
1. What are the conditions for planet formation and the emergence of life?
1.1 From gas and dust to stars and planets
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2. How does the Solar System work?
2.1 From the Sun to the edge of the Solar System
2.2 The giant planets and their environments
2.3 Asteroids and other small bodies

2.1 Formation and Implications for the Solar System and Exoplanets

While there has been debate about Neptune's formation, a leading theory has now emerged from European scientists (e.g. the Nice model of Solar System dynamical evolution, developed at the Observatoire de la Côte d'Azur [Gomes et al., 2005; Tsiganis et al., 2005; Morbidelli et al., 2005]). It is postulated that Neptune formed at around 12-15 AU via planetesimal accumulation, before migrating to its present orbit at ~30 AU through a process of angular momentum exchange with a disk of planetesimals that initially extended out to

30-35 AU, and through interaction with the planets by gravitational scattering [Tsiganis et al., 2005]. This scenario is supported by the higher density of solid material closer to the Sun (typical of protoplanetary disks) that would have lead to a shorter planetary accretion time, and explains the dynamical structure of the Kuiper Belt (~30-50 AU, remnants of the planetesimal disk), the possible occurrence of the cataclysmic late heavy bombardment on the terrestrial planets, and the observed compositional diversity of the asteroid belt.

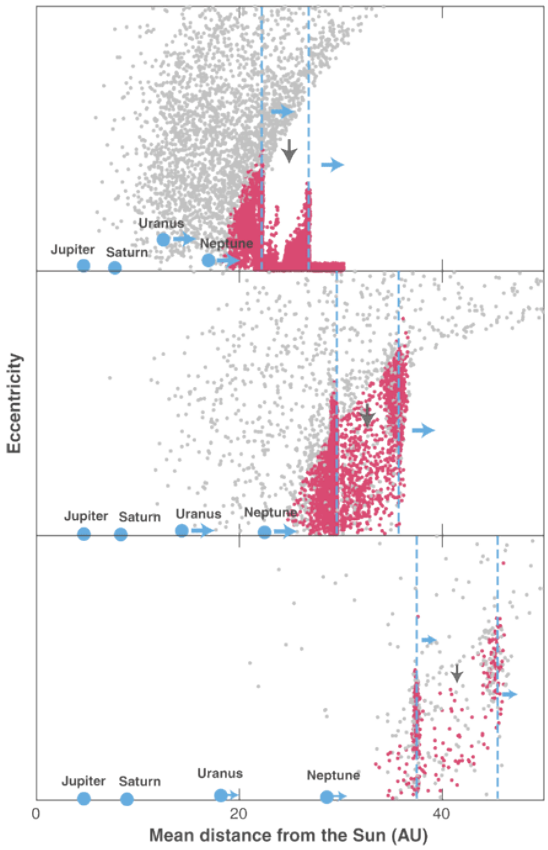

Figure 2. The orbital evolution of the outer Solar System. The three panels show sketches of the beginning, middle, and end of planetary migration. The disk planetesimals are coloured, depending on whether they have had close encounters with Neptune (grey) or not (red). From Morbidelli [2004].

This leading theory highlights the importance of Neptune for Solar System formation and configuration, as illustrated in Figure 2. Neptune effectively pushed the outer boundaries of our Solar System [Morbidelli, 2004]. However, the process by which Neptune formed through accretion of planetesimals is poorly constrained. In addition, present understanding of the composition, configuration, and dynamics of the early Solar System is far from comprehensive, and our best models still cannot explain a number of features of the present day Solar System. Accurate knowledge of the physical properties of Neptune is of paramount importance for progress in all these areas. The size and mass of Neptune's core and its composition (rock/ice fraction) are crucial parameters for the problem of planetary formation, and for revealing the composition of the solar nebula. Knowledge of the properties and composition of interplanetary dust at Neptune's orbit (particularly originating from comets) would also lead to significant progress in this field.

One of the mysteries concerning Neptune's formation stems from the fact that it had to form after Jupiter and Saturn, since it did not accrete as much gas as these two other giant planets. Its core likely reached completion in the later stages of solar nebula evolution, when the gas density was low due to viscous accretion and photoevaporation. How the growth and migration of Jupiter and Saturn delayed the accretion of Neptune's atmosphere is not completely clear [Jakubik et al., 2012]. In this context, a detailed knowledge of the chemistry and composition of Neptune's atmosphere is essential for understanding how and when the planet accreted it.

Focus on Neptune has intensified recently due to the discovery of numerous exoplanets with similar physical characteristics, like Gliese 436 b or GJ 3470 b. In fact, Neptune-sized and sub-Neptune-sized planets are harboured by 3-31% of the Sun-like stars [Fressin et al., 2013]. Therefore Neptune may be typical of the majority of planets beyond our Solar System, unlike Uranus, which appears to have been radically altered by collisional processes. Neptune-sized exoplanets may share a similar evolution with Neptune, and a better knowledge of Neptune's physical properties will shed new light on the formation and characteristics of these exoplanets.

Key scientific questions: How and where did Neptune form? What role did Neptune play in early Solar System dynamics? What does Neptune tell us about the numerous exoplanets of similar mass?

2.2. Interior

Compared to other planets in the Solar System the composition and structure of Neptune's interior is very poorly constrained. The limited current understanding of the Neptunian interior and the high level of uncertainty is illustrated in Figure 3. Progress in this area is essential for answering one of the major mysteries concerning Neptune: Why is heat flux from the interior so high? Multiple theories have been proposed to answer this fundamental question, but without an improved knowledge of the planetary interior we cannot further constrain them. Note that Neptune's internal heat flux is higher than Uranus', representing an important difference between the two ice giant planets. Uranus' low internal heat flux is thought to be the result of collisional processes.

The *Voyager 2* encounter with Neptune provides us with some preliminary constraint on Neptune's internal density distribution, rotation rate, and planetary radius. Before the encounter Neptune's interior was thought to be layered in the form of a rocky core, surrounded by an ice shell and a hydrogen/helium envelope. *Voyager* data indicated a light-element component in Neptune's deep interior, and a transition from a hydrogen/helium-rich to an icy/rock-rich interior at about 60-80% of the planetary radius [Hubbard et al., 1995].

Models constrain the light-element mass fraction in Neptune's deep interior to be 0-30% [Nettelmann et al. 2013], but this range allows for a variety of fundamentally different scenarios. For instance, a low light-element mass fraction of up to 10% could be explained by excess hydrogen originating from an initial water, ammonia and methane-rich composition, which was dissociated under high pressures and underwent phase separation into a hydrogen-oxygen phase and a carbon-nitrogen phase. The latter phase may have produced a diamond core. In contrast, a high light-element abundance would indicate simultaneous accretion of small planetesimals and gas, as well as the presence of rock in the deep interior. The question of hydrogen abundance in Neptune's deep interior and where it metallises is central to understanding how the planet generates its magnetic field.

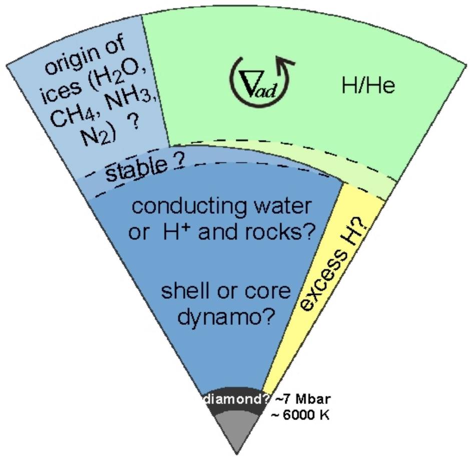

Figure 3. Chart showing Neptune's poorly understood interior.

Another fundamental question about the deep Neptunian interior is whether or not it is convective. All interior models agree in predicting a transition from a hydrogen/helium-rich outer region to a hydrogen/helium-poor inner region. The very deep interior has been suggested to be stably stratified in order to explain what we currently know about the planetary magnetic field thanks to *Voyager*. On the other hand, inefficient internal heat transport over a large fraction of Neptune's interior would yield lower than observed luminosities.

The last of the open issues concerning Neptune's interior that we would like to draw particular attention to is the fraction of heavy elements in the outer envelope, which is related to the fraction of heavy elements in the deep troposphere (the lower atmosphere). Models allow for solar enrichment of oxygen and carbon by a factor ranging between 100 and 400, in agreement with limited measurements of the tropospheric carbon monoxide abundance. In comparison, solar enrichment of heavy elements in the outer envelope of Uranus' interior is thought to be by a factor of 20 or less. It is unclear why the ice giant planets differ in this respect.

Key scientific questions: Why is the heat flux from Neptune's interior so high? What is the size of Neptune's core? What is the rotation rate of Neptune's interior? What is the composition and structure of both the deep interior and outer envelope? Is the deep interior convective?

2.3. Atmosphere

Neptune stands apart from the other giant planets by possessing the most meteorologically active atmosphere in our Solar System, with the fastest winds measured in any planetary atmosphere [e.g. Hammel et al., 1989]. Evidence for Neptune's rapidly evolving atmosphere provided by *Voyager 2* is shown in Figure 4. The drivers of this high level of atmospheric dynamics, given Neptune's distance from the Sun, is a mystery, and is closely related to the puzzle of why the heat flux from Neptune's interior is so high (see Section 2.2). Neptune's level of internal heat flux produces emissions that exceed solar input by a factor of 2.6, the largest of any planet in the Solar System [Pearl & Conrath, 1991]. Comparing Neptune to Uranus once again, Uranus is at the other end of the spectrum, with a ratio of only 1.1.

While Neptune's troposphere is likely driven by this excess of internal heat, it is unknown exactly what processes are involved, and how important surface effects are [Kaspi et al., 2013]. In addition, the power available to drive Neptune's incredibly strong wind systems is 20 times less than that at Jupiter. Some of the basic dynamical, chemical, and cloud-forming processes at work within Neptune's churning atmosphere, along with the competing influences of seasonally changing insolation and internal heat flux on the atmospheric structure, are unknown.

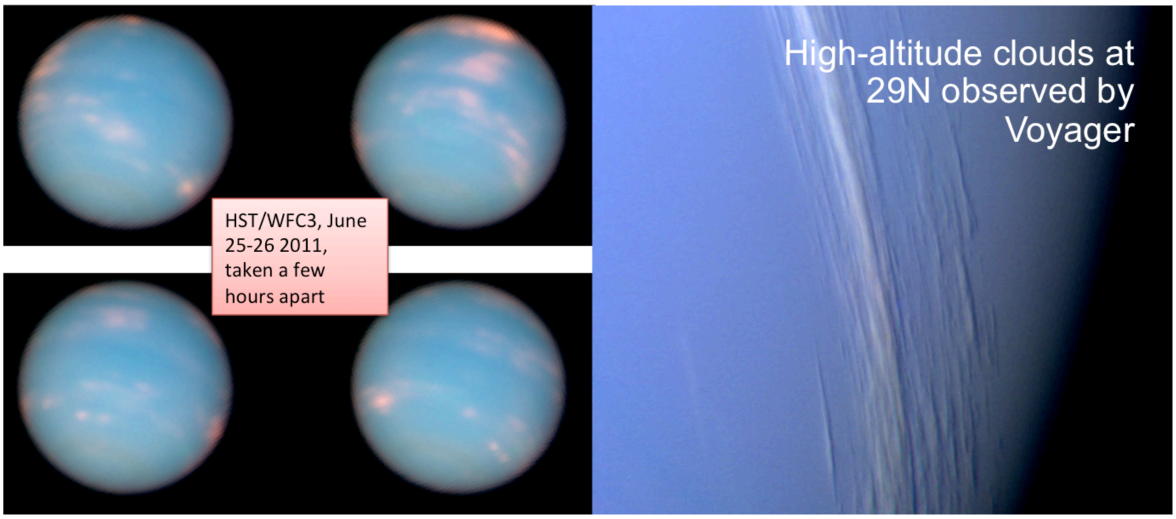

Figure 4. Hubble Space Telescope images of Neptune's rapidly evolving cloud systems, taken just a few hours apart (left). High-altitude clouds seen by Voyager 2 (right), credit: NASA/JPL.

Our present understanding is that Neptune's atmospheric composition is controlled by condensation chemistry, vertical mixing, external influx of oxygenated species from infalling comets and dust, and a rich hydrocarbon photochemistry due to the ultraviolet destruction of methane. Compared to Jupiter and Saturn, Neptune appears to have a different relation between banded cloud structures, atmospheric temperatures, and zonal wind structure. Infalling dust particles (e.g. interplanetary dust) are expected to pollute Neptune's atmosphere.

Rapidly evolving convective cloud activity prevails at cooler mid-latitudes (see Figure 4), with retrograde flow at the warmer equator and a high-latitude prograde jet confining a seasonally variable polar vortex of unusually high temperatures and unique chemical composition. Dark ovals (such as the Great Dark Spot observed by *Voyager 2*) are enormous storm systems, and are sometimes associated with bright white orographic clouds at higher altitudes. Neptune's strong zonal winds suggest a possibly low level of atmospheric turbulence that leads to energy dissipation. A reduced level of atmospheric turbulence would be in stark contrast to the fully turbulent atmospheres of Jupiter and Saturn.

The three-dimensional composition and structure of the atmosphere is unclear, and is central to understanding atmospheric chemistry [e.g. Lellouch et al., 1994] and cloud formation. Profiles of temperature, density, gaseous composition and aerosols would hold the key to understanding the balance between internal heating, convective mixing, latent heat release, and radiative heating and cooling throughout Neptune's atmosphere. In addition, the poles are important regions for the Neptune atmosphere problem, as they are the sites of coupling to the planet's magnetosphere (see Section 2.5). As is the case with other giant planets in our Solar System, the high temperature of Neptune's upper atmosphere remains to be explained.

Key scientific questions: What drives dynamics in the most meteorologically active atmosphere in our Solar System? What is the composition and structure of Neptune's atmosphere? What powers storm systems in Neptune's atmosphere? What is the nature of atmospheric chemistry and cloud formation?

2.4. Rings and Small Icy Satellites

Although all giant planets shelter a ring system, Neptune's ring system is unique because it consists of a collection of concentric and semi-transparent ringlets embedded in a tenuous sheet of dust. The Neptunian rings are tightly gravitationally coupled to a rich system of moonlets. Between the ringlets orbit a number of small moons (Naïad, Thalassa, Despina, Galatea). Both the rings and moons are especially dark, and the coupling between them is likely to be of key importance. The rings contain up to 70% dust in some regions [Smith et al., 1989], which makes them fundamentally different from Saturn's rings, which contain less than

1% dust. The origin of this difference in composition is still a mystery, and could be the signature of different formation/evolutionary processes.

High-resolution imaging carried out by *Voyager 2* suggests that some rings have sharp edges despite viscous spreading, suggesting gravitational confinement effects. Other rings appear to be broken into arc-like structures, as shown in Figure 5, which are somehow able to survive despite tidal forces and collisions between ring particles. The confinement effect of one or several nearby moons has been invoked to explain this. Earth-based observations have revealed the dynamical nature of the rings, and showed in 1999 that some arcs had shifted significantly from their expected location [Sicardy et al., 1999], while others seem to have fluctuated strongly in brightness since the *Voyager* era. Although the Jovian and Saturnian systems have moon-driven, extended, diffuse ring systems, currently no data exists about the Neptunian environment [Krivov et al., 2002; Srama et al., 2006].

Figure 5. Image of the Adams and Leverrier ring (outer and inner curve, respectively) taken by the Voyager 2 wide-angle camera. The brightest parts of the Adams ring are the ring arcs. Credit: NASA/JPL.

The driver(s) of ring dynamics are unclear, and widely debated. It is thought that Neptune's rings evolve under the coupled action of sunlight, gravity, and collisional processes, but why their evolution is so different from other planetary ring systems is unknown. One of the most exciting perspectives about their origin is that they could be the result of disrupted satellites, either by tides [Leinhardt et al., 2012] or by cometary impacts [Colwell & Esposito, 1990]. A re-accretion process might currently be operating.

Neptune has 6 regular moons orbiting within 5 planetary radii, forming a compact system reminiscent of Saturn's mid-sized moons. A good fraction of them seem to orbit inside Neptune's Roche limit for ice, which implies that the small moons may be denser than ice [Tiscareno et al., 2013]. Tidal disruption of the weakest moons could give birth to narrow rings [Leinhardt et al., 2012]. Neptune's regular satellites are barely characterised, and their mass and densities are simply inferred from model-dependent arguments concerning the evolution of the rings. The surface of Proteus, the largest of Neptune's inner satellites, appears to be densely cratered, and its non-hydrostatic shape may be the signature of past collisions, as illustrated by its large crater Pharos. The surfaces of the four innermost moons have never been imaged, representing a serious gap in our knowledge of the Neptune planetary system.

Satellite surfaces are continuously exposed to the interplanetary and interstellar meteoroid background, and ejecta from moon surfaces generates surrounding dust clouds, potentially creating ring systems [Krivov et al., 2002], and it has been proposed that the rings might have played a role in building the satellites themselves [Crida & Charnoz, 2012]. What is clear about this barely understood inner region of the Neptune system is that answering the many open questions about either the rings or inner moons would have important implications for the other.

Key scientific questions: Why is the composition of Neptune's rings different to that of any other planetary ring system? How do the ring arcs survive? Does Neptune have extended, dusty rings like Jupiter and Saturn? How did Neptune's inner satellites form? How does the coupled ring-moon system work?

2.5. Magnetic Environment

Neptune's magnetic field has a complex geometry. There is a large angle of ~47° between the magnetic dipole and rotation axes of the planet, the field is significantly offset from the centre of the planet by ~0.5 Neptune radii (R_N), and non-dipolar components are significant [e.g. Connerney et al., 1991]. The single *Voyager 2* flyby provides us with only a basic understanding of the field structure. Combining this with the fundamental unknowns concerning the planetary interior (see Section 2.2) makes the origin of Neptune's unusual magnetic field unclear. Solving the problem of how Neptune generates its magnetic field is a major challenge for dynamo theorists, with broad implications for the field of planetary magnetism [e.g. Stanley & Bloxham, 2004; Soderlund et al., 2013].

The nature of Neptune's magnetic field leads to a highly irregular magnetosphere surrounding the planet [Bagenal, 1992]. The competition between the pressure exerted by the flow of solar wind plasma from the Sun and the pressure exerted by Neptune's magnetic field produces a substantial magnetospheric cavity in the solar wind flow that envelopes most of the Neptunian satellites, including Triton. Neptune's large dipole tilt angle leads to dramatic diurnal changes in the magnetosphere, unlike any other magnetosphere explored in detail to date. The changing configuration of Neptune's magnetosphere is illustrated in Figure 6.

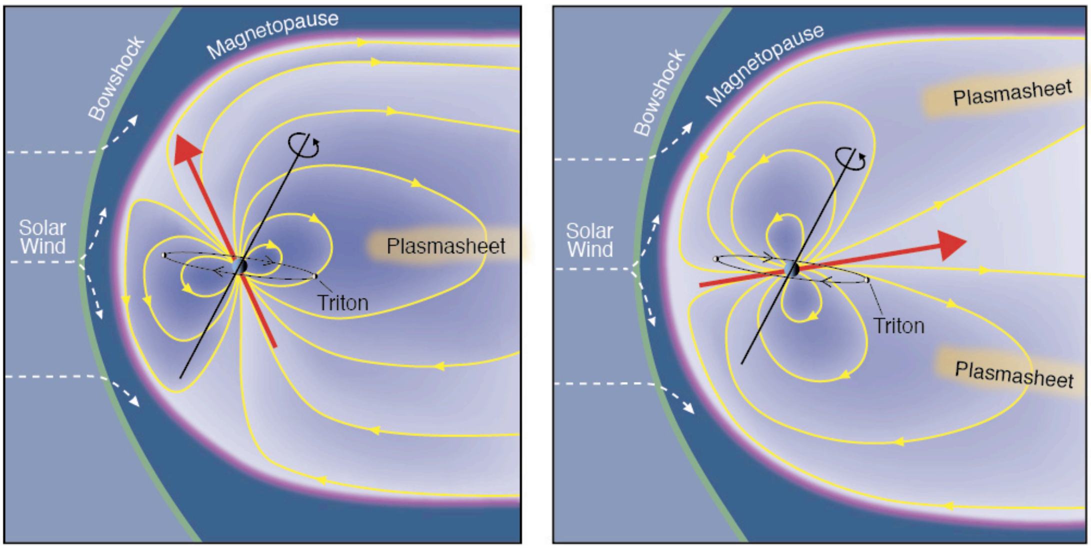

Figure 6. The changing configuration of Neptune's magnetosphere under solstice (southern summer) conditions. The noon-midnight plane is shown, with the planetary dipole (red arrow) captured at positions separated by half a planetary rotation period. Credit: Steve Bartlett & Fran Bagenal.

There are numerous important questions about how Neptune's magnetosphere works, which are also highly relevant for understanding the planetary atmosphere, rings, and satellites. Uncertainty surrounds the question of how the magnetosphere changes so dramatically in only half a planetary rotation period (~8 hrs), and what this means for the coupling between various parts of the system. This dynamic nature means that Neptune's magnetosphere may be our best Solar System laboratory for studying charge separation and equilibration due to variable magnetic fields, and the timescales associated with different particle acceleration mechanisms.

The relative importance of sources and sinks of plasma in Neptune's magnetosphere is also unknown. Triton is thought to be an important source [Richardson et al., 1991] (see Section 3), as well as dust particles. Triton makes the Neptunian magnetosphere a vital link between magnetospheres with similar internal sources of plasma but simpler internal fields (Jupiter and Saturn), and those with similar magnetic complexity but lacking these sources (Uranus). In particular, the presence/absence of a Triton plasma torus may explain the mysterious lack of a clear torus in Saturn's magnetosphere due to the moon Titan. Strong dust-plasma interactions may produce charged dust streams like those at Jupiter and Saturn [e.g. Kempf et al., 2005].

Auroral radio emission with distinct components has been unambiguously identified [e.g. Zarka et al., 1995] as well as emission at other wavelengths [Bhardwaj & Gladstone, 2000]. Otherwise, Neptune's auroral emissions are among the most mysterious in the Solar System, yet essential for understanding Neptune's magnetospheric system and the atmospheric energy budget. As the furthest planet from the Sun, how Neptune's dynamic magnetosphere interacts with the solar wind is of great interest [e.g. Schulz et al., 1995]. The planetary bow shock wave that stands upstream of the magnetosphere in the solar wind flow is expected to be the strongest (highest Mach number) in the heliosphere, and the magnetopause boundary of Neptune's magnetosphere is a unique laboratory in which to study fundamental processes (e.g. magnetic reconnection).

Key scientific questions: What is the origin and structure of Neptune's complex magnetic field? How does the magnetosphere re-configure on such short timescales? What are the sources and sinks of magnetospheric plasma? How does Neptune's aurora work? How does Neptune's magnetosphere interact with the solar wind?

3. Triton

Relevant ESA Cosmic Vision scientific questions:
1. What are the conditions for planet formation and the emergence of life?
1.1 From gas and dust to stars and planets
1.3 Life and habitability in the Solar System
2. How does the Solar System work?
2.2 The giant planets and their environments
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3.1 Origin and Implications for the Neptune System

Triton, by far the largest of Neptune's moons, dominates Neptune's satellite system, and is an object of tremendous scientific interest. Triton's inclined (157°) retrograde orbit strongly suggests that it was captured by Neptune at some point during its history, as illustrated in Figure 7 [Goldreich et al., 1989; McKinnon et al., 1995; Agnor & Hamilton, 2006]. Thus, Triton likely formed orbiting the Sun in a similar region as other icy dwarf planets and primitive bodies in the outer Solar System, such as Eris, Pluto, Makemake, Haumea, Sedna, Orcus, and Quaoar.

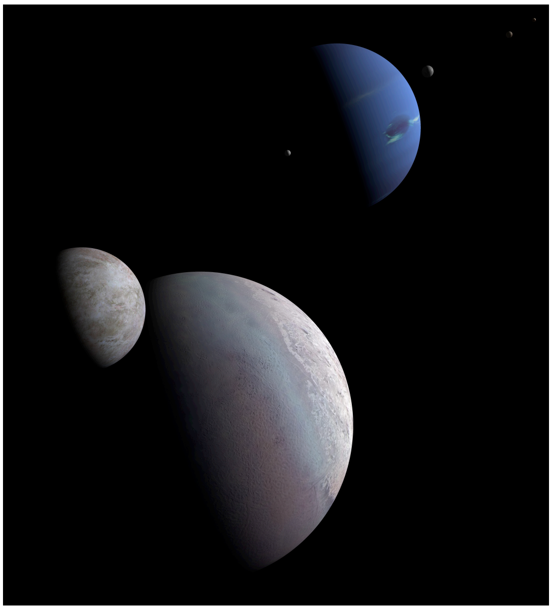

Figure 7. Triton and its binary companion as they approached Neptune. This encounter lead to Triton's capture by Neptune, an event that catastrophically altered the Neptune satellite system. In the image Neptune is orbited by several primordial satellites that may have existed prior to the encounter, but were destroyed in its aftermath.

This makes Triton the only large moon in the Solar System that did not form around its host planet. The physical characteristics (e.g. composition) of Triton hold the key to understanding the icy dwarf planets of the distant Kuiper Belt, an opportunity that no other planetary system can claim. Triton is subject to the tidal, radiolytic, and collisional environment of an icy satellite, but with the initial composition of a Kuiper Belt object.

Triton's capture must have left it on an orbit that was much larger (orbital radius: ~80-1,000 R_N) and more eccentric (eccentricity: >~0.95) than its current one (orbital radius: 14 R_N, eccentricity: 0). Triton's post-capture evolution likely dominated the subsequent evolution of the Neptunian system, and subjected the planetary satellite system to extreme processing via catastrophically disruptive collisions, gravitational scattering and tidal heating.

Driven to crossing orbits by Triton's perturbations, Neptune's inner satellites would collide at such large velocities that they would suffer catastrophic disruption and grind each other down into a debris disk [Goldreich et al., 1989]. In this view, Neptune's inner satellites are either the shards left over from this process or second-generation satellites that accreted from the rings and debris disk [Crida & Charnoz, 2012] (see Section 2.4). In either case, the inner satellite system has experienced extreme collisional processing. Neptune's distant irregular satellites were gravitationally sculpted by Triton following its capture with satellite material being exchanged between the inner and outer regions through a variety of dynamical mechanisms.

Triton itself may have accumulated a significant portion of its mass (~>20%) from the debris disk [Cuk & Gladman, 2005]. The accretion of this material would have hastened Triton's orbital decay, and would suggest that it may be a composite of heliocentric and planetocentric material. Triton's orbital decay was dominated by tidal friction, and the heating during this epoch is expected to be sufficient for global melting of Triton, and the formation of subsurface oceans [McKinnon et al., 1995].

Key scientific questions: Does Triton retain any physical memory of its origins as an icy dwarf planet? How did Triton evolve after it was captured, and how did Triton affect the Neptune planetary system? What are the similarities and differences between Triton and the dwarf planets of the Kuiper Belt?

3.2 Interior and Surface

The current state of our knowledge of Triton is based on very few observations (*Voyager 2*) and models. As a result, everything we think we know is subject to significant uncertainty, and there are fundamental questions that we have no answer to at present. What little we know implies that Triton is composed of a high proportion of rock and metal (~65-70%) compared to ice. Triton's orbital history and surface geology suggest an important role for tidal heating in the past [e.g., McKinnon et al., 1995] (see Section 3.1), which may have produced a differentiated interior with separation of ices, rocks, and metals. Triton could have a metallic core, silicate mantle, and internal liquid ocean between ice layers [Hussmann et al., 2006; McKinnon & Kirk, 2007].

The brittle lithosphere (the outermost region of Triton's interior) is estimated to be ~10-15 km thick [Ruiz, 2003], which implies heat flows at the time when the surface was deformed that were clearly higher than those associated with the total radioactive heat production in the rocky portion of the satellite. Thus, observed resurfacing, geological activity, and the relatively thin lithosphere could have been caused by the heat generated during the capture of Triton, or by later release of the remaining heat.

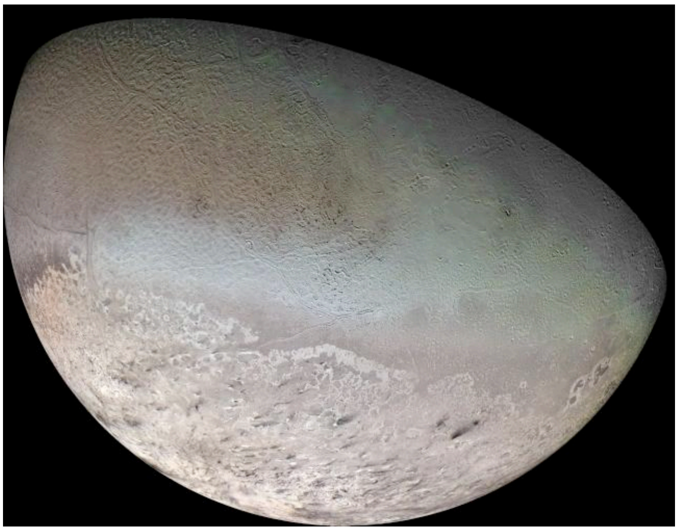

Figure 8. Global mosaic of Triton's surface. The southern polar cap covers the lower part of the imaged region of the surface. At lower latitudes the cantaloupe terrain and plains are in the West and the East, respectively. Credit: NASA/JPL/USGS.

Triton's surface is composed of ices, mostly N_2 (which includes CO, CH_4, and C_2H_6 in solution), with seasonal polar deposits, plus H_2O, and CO_2 [Quirico et al., 1999]. Triton's surface has a young appearance, indicated by the sparseness and limited size of unambiguous impact craters, and by a variety of terrains unique to icy satellites. Crater counts indicate a surface age of several tens to hundreds of millions of years, but that in places the surface age could be as young as a few million years [Stern & McKinnon, 2000; Schenk & Zahnle, 2007]. Triton's surface is one of the younger surfaces in the Solar System, and shows that Triton is a geologically active satellite.

On Triton's surface there are two major types of geological terrains [Smith et al., 1989; Croft et al., 1995], and a large polar cap of solid nitrogen ice covers a significant fraction of the southern hemisphere. Figure 8 shows *Voyager 2* imaging of the different terrain types. A substantial portion of the surface away from the polar cap that could be imaged by *Voyager 2* during its flyby appears to be occupied by expanses of regularly spaced, nearly circular depressions, dubbed cantaloupe terrains. The depressions are a few tens of kilometres wide and have a complex morphology. The other terrain type is undulating or smooth plains that show a variety of landforms, including depressions filled with smooth materials and "ice lakes". The surface is also deformed by a global network of ridges and troughs, more visible on the cantaloupe terrains and partly flooded at some locations on the plains [Croft et al., 1995]. The ridges morphologically resemble those seen at Jupiter's moon Europa [Prockter et al., 2005], although they are much less numerous.

Voyager 2 observed at least two plumes of nitrogen gas and dust at Triton's southern polar cap, which erupted from beneath the surface, extended up to 8 km above it, and were then dragged by atmospheric winds [Soderblom et al., 1990] (see Section 3.3). The polar dark streaks may be a result of such plume activity.

Key scientific questions: What are the composition, structure, and heat flow from Triton's interior? What is the age of features on Triton's surface? How geologically active is Triton and what drives the plumes?

3.3 Atmosphere

Triton's tenuous atmosphere was discovered by *Voyager 2*, although more distant remote sensing provided indirect evidence for an atmosphere before the flyby. We know only basic properties of the atmosphere, and how Triton's atmosphere interacts with both the surface of the moon below, and Neptune's magnetosphere above, remains unclear. Yet these properties are essential for understanding energy flow though the coupled planet-moon system.

Triton's atmosphere appears to be nitrogen-rich, and sustained by ices at the surface in vapour pressure equilibrium with the atmosphere. It has been likened to the atmosphere of Pluto. Currently known additional species in Triton's atmosphere are trace amounts of volatile gases, including methane and carbon monoxide. Trace amounts of CH_4, less than those in the atmospheres of Saturn's moon Titan or Pluto, were discovered using ultraviolet observations made by *Voyager* [Broadfoot et al., 1989]. CO was first observed using the European Southern Observatory Very Large Telescope [Lellouch et al., 2010].

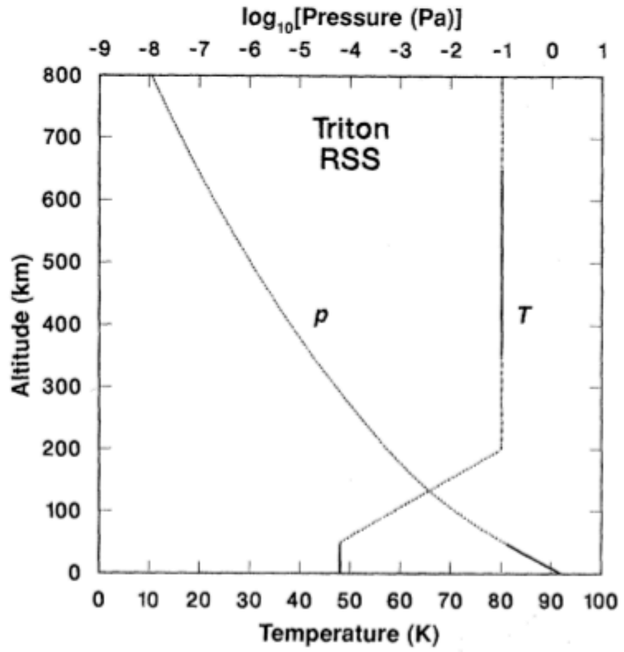

Figure 9. Profile of Triton's atmosphere based on radio data and models. From Tyler et al. [1989].

A profile of Triton's atmosphere is shown in Figure 9. Surface atmospheric pressure is thought to be ~1.4-1.9 Pa (14-19 μbar) [Broadfoot et al., 1989, Tyler et al., 1989]. Pressure equilibrium in the nitrogen-rich atmosphere implies an upper limit for the surface temperature of Triton of ~38 K. Triton's atmosphere is seasonally variable, as the CH_4 abundance observed recently was several times that observed by *Voyager* [Lellouch et al., 2010].

Turbulence at Triton's surface creates a troposphere (lower level of the atmosphere) up to 8 km. Streaks on Triton's surface left by plumes (see Section 3.2) suggest that the troposphere is driven by seasonal winds capable of moving material over ~1 μm in size [Smith et al., 1989]. Triton lacks a stratosphere, but has a thermosphere between ~8 and ~950 km, and an exosphere above. The temperature of the upper atmosphere is ~95 K, higher than that at the surface, which is thought to be due to heat absorbed from solar radiation and precipitation from Neptune's magnetosphere [Broadfoot et al., 1989]. A haze permeates most of Triton's troposphere, which may be largely composed of hydrocarbons and nitriles created by the action of sunlight on methane. The Triton atmosphere also appears to possess clouds of condensed nitrogen that lie between 1 and 3 km from the surface [Smith et al., 1989].

Key scientific questions: What molecular species are present in Triton's atmosphere? What is the distribution and source of aerosols in the atmosphere? How do winds affect the structure of Triton's atmosphere? What are the properties of the nitrogen plumes? What is the rate of dust infall to Triton's atmosphere?

3.4 Interaction with the Magnetosphere

Triton is thought to be the major source of plasma in Neptune's dynamic and irregular magnetosphere [Richardson et al., 1991] (see Section 2.5); however, the relative strength of Triton as a source compared to the solar wind and Neptune's ionosphere is unclear. Because of Triton's remarkable retrograde and highly inclined orbit, coupled with the dramatic diurnal reconfigurations of the planetary magnetosphere, the interaction between Triton and Neptune's magnetosphere is unique in the Solar System, and may be key to understanding the electrodynamics of moon-magnetosphere interactions in other planetary systems.

Triton has an ionosphere at the top of its tenuous atmosphere with a peak density at ~340km, as determined by radio science observations. One surprise revealed by these data was the observed high ionospheric density of

~46,000 cm^{-3} [Tyler et al., 1989]; this is higher than that in the ionosphere of Saturn's moon Titan, which also has a nitrogen-based atmosphere. This is surprising because the solar illumination is a factor of ~10 lower at Triton than at Titan. The high density has been suggested to be due to the impact of energetic (>10 keV) precipitating particles from Neptune's magnetosphere [Strobel et al., 1990]. The measured energy flux of >22keV particles well away from Triton is ~2 orders of magnitude greater than sunlight [Krimigis et al., 1989], but this will reduce significantly when Triton is far from the planetary magnetic equator.

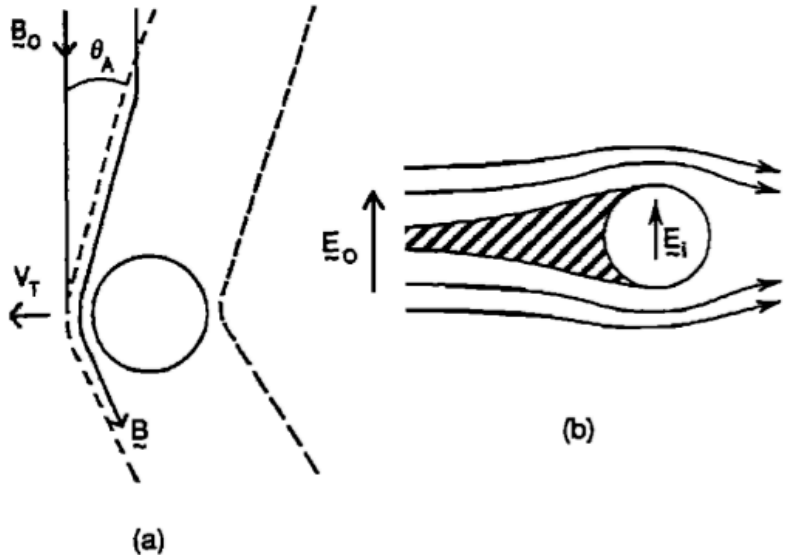

Figure 10. Triton's magnetospheric interaction, showing the expected Alfvén wings. From Strobel et al. [1990].

Due to the geometry and closest approach distance of the *Voyager 2* encounter with Triton, the moon-magnetosphere interaction has never been measured directly. Triton regularly visits different regions of Neptune's magnetosphere (magnetic L-shells between 14.3 and >>40 R_N [Ness et al., 1989]) and is subject to different particle fluxes, and thus different coupling between the magnetosphere, atmosphere, and possibly Triton's surface. There is also a complex seasonal cycle, which must provide interesting and possibly significant effects.

Triton's orbital speed (4.4 kms^{-1}) and the expected local speed of magnetospheric plasma flow (~40 kms^{-1}) mean that Triton's interaction is likely to be transonic and sub-Alfvénic [Neubauer, 1990, Strobel et al., 1990]. These conditions are similar to those at Jupiter's moon Io. As a result, Alfvén wings are anticipated at Triton, as illustrated in Figure 10. Any intrinsic or induced (e.g. due to a subsurface ocean) magnetic fields at Triton would clearly affect this interaction with the magnetosphere.

Key scientific objectives: Why is Triton's ionosphere so dense, and what production and loss processes are involved? What is the nature of the Triton-magnetosphere interaction, and how does it respond to constantly changing external conditions? How important is Triton as a source of magnetospheric plasma? Does Triton have an internal magnetic field or aurorae? To what extent do energetic particles penetrate the atmosphere?

3.5 Habitability

Since the era of the *Voyager* planetary encounters subsurface oceans have been identified at three of Jupiter's moons (Europa, Ganymede, and Callisto), and there is indirect evidence for two of Saturn's moons (Enceladus and Titan) [e.g. Kivelson, 2004]. Subsurface oceans may be a common feature of icy moons in the Solar System, and a subsurface water ocean is predicted at Triton [McKinnon et al., 1995; Hussmann et al., 2006; McKinnon & Kirk, 2007]. Water is thought to be a key requirement for the habitability of such an ocean. *Cassini* observations at Saturn's moon Enceladus have demonstrated that dust in the surrounding environment can potentially reveal the composition of any subsurface ocean [Postberg et al., 2011].

As we have seen in Section 3.2, Triton has a young surface, with active cryovolcanism likely. This is evidence for the interplay between tidal dissipation, heat transfer, and tectonics which provides the energy for resurfacing of Jupiter's satellites Europa and Ganymede and at Saturn's satellite Enceladus. Such a source of energy is another expected requirement for the habitability of a subsurface ocean. Remaining expected habitability requirements are the right chemical environment, and time. Our limited knowledge of Triton's surface and atmospheric composition are the major constraint in our assessment of Triton as a potential habitat. Whether a subsurface ocean exists as predicted and whether there is any chemical evidence for this on the surface or in the atmosphere are major open questions concerning Triton, highly relevant for the field of astrobiology.

Key scientific questions: Does Triton have a subsurface ocean, and, if so, what are its properties and composition? Is the chemical environment favourable for habitability? How does Triton compare to other Solar System moons of astrobiological interest?

4. Science During an Interplanetary Transfer to the Neptune System

Relevant ESA Cosmic Vision scientific questions:
2. How does the Solar System work?
2.1 From the Sun to the edge of the Solar System
3. What are the fundamental physical laws of the Universe?
3.1 Explore the limits of contemporary physics

Answering the fundamental questions across multiple fields of planetary science that are outlined in Sections 2 and 3 require further spacecraft exploration of the Neptune system, as will be discussed in Section 5. Because of this, in this section we highlight the important additional scientific questions that could be addressed by a spacecraft on an interplanetary transfer to Neptune. This further extends the broad range of scientific fields covered by the theme of Neptune-Triton science.

Interplanetary and interstellar dust pervade the Solar System, but their distribution is not well known. Revealing the properties of this dust from 1 to 30 AU would have implications for Solar System formation and evolution (see Section 2.1), providing information about the Kuiper Belt. Interstellar dust grains are of particular interest as they are expected to preserve the conditions of star formation [Altobelli et al., 2003].

The continuous flow of solar wind plasma away from the Sun leads to significant energy flux through our entire Solar System, and this plasma flow eventually encounters its heliopause boundary. However, very few solar wind measurements have been made in the outer Solar System, beyond 10 AU. How solar wind structures (e.g. coronal mass ejections), evolve from the Sun to Neptune is therefore a largely open question in heliospheric physics. In addition, energetic neutral atoms have never been detected in the distant Solar System where Neptune resides, and would shed light on the global structure of the heliosphere itself.

Interplanetary space approaching Neptune is of great importance as an environment in which we can test the limits of contemporary physics. General Relativity (GR), the current theoretical formulation of gravitation, is in good agreement with most experimental tests [Will, 2006]. However, GR is a classical theory, and all attempts to merge it with the quantum description of the other fundamental interactions suggest it cannot be the final theory of gravitation. Meanwhile, experimental tests leave open windows for deviations from GR at small [Adelberger et al., 2009] and large distances [Reynaud & Jaekel, 2005].

GR is also challenged by observations at galactic and cosmic scales. The rotation curves of galaxies and the relation between redshifts and luminosities of supernovae deviate from the predictions of the theory. These anomalies are interpreted as revealing the presence of new components of the Universe, so-called "dark matter" and "dark energy" [Copeland et al., 2006; Frieman et al., 2008] which are thought to constitute respectively 25.8% and 69.4% of the energy content of the Universe according to most recent estimates [Ade et al., 2013]. The nature of both dark matter and energy remains unknown, and, despite their contribution to total energy content, they have not been detected up to now by means other than gravitational measurements.

A crucial question when addressing the nature of dark matter and dark energy is whether or not GR is the correct description of gravity at large scales, like distances approaching that between the Sun and Neptune. Addressing this question is essential in order to bridge the gap between experiments in the Solar System and astrophysical or cosmological observations. Probing the limits of current gravitation theory is also clearly related to the problem of Solar System formation and evolution, including the formation of the Neptune planetary system (see Section 2.1).

Key scientific questions: How do dust properties vary from Earth to Neptune? Do solar wind properties in the outer Solar System agree with model predictions? How do solar wind transients evolve from the Sun to ~30 AU, and what does this mean for Neptune's magnetospheric dynamics? Is general relativity the correct description of gravity at scales approaching the Sun-Neptune distance? If not, how does this change our understanding of Solar System formation and evolution, and the dark matter/dark energy problem?

5. Neptune-Triton Mission Concepts

The driver of this white paper is the broad range of fundamental scientific questions that can be addressed in the Neptune planetary system (highly relevant for ESA's Cosmic Vision), which make Neptune and Triton strategic targets for planetary scientists. In this section we present a high-level discussion of the possibility of an ESA L-class mission to Neptune. Identifying enabling technology is a priority. The cost of an ESA Neptune mission would likely be similar to *JUICE*, within the L-class mission framework.

The tremendous scientific potential of Neptune and Triton has been known for many years, and has lead to multiple mission concepts being studied in great detail. Heritage is provided by the most recent NASA/JPL mission concept study, which considered a range of mission architectures [Marley et al., 2010], and also from the Outer Solar System Mission that was submitted to ESA in response to the most recent call for M-class mission proposals [Christophe et al., 2012]. There is a great deal of scope for international collaboration, and also potential to use *JUICE* hardware in a spacecraft bound for Neptune.

5.1 Mission Architecture and Payload Options

To address all the diverse scientific questions outlined in Sections 2 to 4 a mission to Neptune requires a Neptune-orbiting spacecraft that makes multiple Triton flybys. If equipped with a payload of modern spacecraft instrumentation, such a spacecraft in orbit around Neptune would allow all questions to be addressed. Possible additional mission elements are a Neptune atmospheric descent probe, a Triton lander, and additional spacecraft; however, the inclusion of these enhancing elements is likely to be limited by mission cost and technical feasibility, and so they are not considered here. Such elements could potentially be considered in the framework of an international collaboration programme.

There are similarities between the Neptune orbiter discussed here and the *Galileo* and *Cassini-Huygens* missions to Jupiter and to Saturn and Titan, respectively. In both these cases the first spacecraft to orbit each planet lead to/continues to provide a hugely significant, paradigm-changing scientific return. A Neptune orbiter carrying a similar payload of scientific instruments would cover the wide range of Neptune-Triton science themes. Table 1 lists payload options. All modern spacecraft instrumentation included in Table 1 have a high Technology Readiness Level (TRL) and significant flight heritage. All values for instrument mass and power consumption are estimates. Specific measurement requirements for a Neptune orbiter mission are not discussed here, although the measurement ranges of heritage instruments would very likely be appropriate.

Instrument	**Mass (kg)**	**Power (W)**	**Heritage**
Narrow-angle camera (NAC)	9.8	14.0	Mars Express (SRC), New Horizons (LORRI), JUICE (JANUS)
Visible-infrared imager (VIR)	10.1	7.5	New Horizons (Ralph), Mars Express (OMEGA), Rosetta (VIRTIS), BepiColombo (SIMBIO-SYS)
Ultraviolet imaging spectrometer (UVIS)	5.0	12.0	BepiColombo (PHEBUS), Mars Express (SPICAM-UV), JUICE (UVS)
Accelerometer (ACC)	3.5	3.0	GOCE, GRACE, BepiColombo (ISA)
Radio science experiment (including ultrastable oscillator) (RSE)	3.5	45.5	Rosetta (RSI), New Horizons (REX), BepiColombo (MORE), JUICE (3GM)
Magnetometer (MAG)	3.3	3.0	Cassini (MAG), Double Star (MAG), Rosetta (RPC), BepiColombo (MERMAG), JUICE (J-MAG)
Thermal imager (TMI)	7.0	20.0	BepiColombo (MERTIS)
Particle package (plasma, neutrals, energetic neutral atoms) (PP)	23.0	50.0	Cassini (CAPS, MIMI), New Horizons (SWAP, PEPSSI), JUICE (PEP)
Radio and plasma wave system (RPWS)	5.7	7.1	Cassini (RPWS), JUICE (RPWI)
Dust Analyser (DA)	3.2	8.0	Cassini (CDA), Stardust (CIDA)

Table 1. Neptune orbiter payload options. All values of instrument mass and power consumption are estimates based on heritage instruments.

Science theme	NAC	VIR	UVIS	ACC	RSE	MAG	TMI	PP	RPWS	DA
Neptune interior (2.2)				■	■	■			■	
Neptune atmosphere (2.3)	■	■	■				■		■	■
Neptune rings and icy satellites (2.4)	■	■	■		■	■		■	■	■
Neptune magnetic environment (2.5)		■	■			■		■	■	
Triton interior and surface (3.2)	■	■	■	■	■	■	■			■
Triton atmosphere (3.3)	■					■		■	■	■
Triton-magnetosphere interaction (3.4)		■	■			■		■	■	
Cruise science (4)				■	■	■		■	■	■

Table 2. Matrix relating science themes to payload options. Numbers given in brackets after each science theme indicate the relevant section/sub-section of this white paper.

Including all these instruments would result in a total payload mass of ~70 kg, compared to the ~60 kg value associated with a Neptune orbiter mission architecture previously studied by NASA [Marley et al., 2010]. Instrument development between now and the L2/L3 timeframe will likely reduce both mass and power consumption. Note that the instrument radiation shielding requirements are significantly lower for a Neptune orbiter compared to ESA's *JUICE* mission. We suggest that a programme of instrument studies within Europe's potential payload-providing countries be considered. Table 2 shows how each instrument included in Table 1 would address the various Neptune-Triton science themes discussed in this white paper (dependent on instrument specifications). Neptune formation (Section 2.1), Triton origin (Section 3.1), and Triton habitability (Section 3.5) science themes are not included in Table 2 because, while each is a distinct science theme, answering major science questions in these areas is dependent on answering those in other (included) areas.

5.2 Enabling Technology

Extended Deep Space Network (DSN) capability

Ka and X bands would be used for data and telemetry for a Neptune orbiter mission. The previous Neptune orbiter study by NASA [Marley et al., 2010] showed that a Ka-downlink to a single 34-m antenna yields 1-6 kbps at Neptune. A suggested solution to improve the data rate consisted of using four arrayed 34 m antennas. Although technology studies have been perfromed by ESOC, plans do not currently exist for multiple 35-m antennas in a single location of the European Tracking Network. However, plans exist within NASA's Deep Space Network (DSN). Use of the future DSN capability by ESA under a cooperation agreement would allow a data rate sufficient for a Neptune orbiter mission.

Radioisotope Thermoelectric Generators (RTGs) or Stirling Radioisotope Generators (SRGs)

The issue of electrical power for any mission beyond Jupiter makes RTGs or SRGs an enabling technology for a Neptune orbiter. European RTG development activities are currently targeting a maximum electrical power output of 50 W, with SRGs targeting 100 W. The European program to develop RTGs is currently at TRL ~3 [Ambrosi et al., 2013]. The radioisotope chosen for the European space nuclear power program is Americium-241 [Sarsfield et al., 2013], which has a longer half-life than the Plutonium-238 that has been used in almost all past RTGs employed in space. The current European RTG lifetime requirement is 20 years. Although there are differences between past and present RTG systems and the European units under development, we note that all past space RTGs have exceeded lifetime requirements (e.g. *Cassini-Huygens*). If we take the nominal power requirement of a Neptune orbiter mission to be 500 W, 10 European RTGs would be sufficient, producing a total electric power of 500 W for a total mass of ~250 kg. This assumes a nominal specific power of 2.0 W/kg, which is the current target of a study led by a UK team [Ambrosi et al., 2013]. Assuming a 20% maturity margin, the total mass would be ~300 kg. For comparison, a previous Neptune orbiter study by NASA [Marley et al., 2010] included 2 ASRGs (and 1 redundant) for a total power of ~280 W (100 kg). *JUICE* uses solar arrays to produce ~640 W at end of life (~350 kg for the entire subsystem) [Dougherty et al., 2011].

Solar Electric Propulsion (SEP)

An RTG lifetime comparable to interplanetary transfer time leads to a third enabling technology for a Neptune orbiter mission. Options to reduce the interplanetary transfer time are an SEP module, an Electric Sail (E-sail), and aerocapture at Neptune Orbit Insertion (NOI). The option with the highest TRL is SEP, which would provide large Delta-V with small propellant mass in the earlier part of an interplanetary transfer to Neptune (see Section 5.3), before module ejection prior to NOI. An SEP module with four QinetiQ T6 Gridded Ion Engines (3 nominal and 1 redundant) would be sufficient, each providing 155 mN of thrust and requiring 5.5 kW. These high-TRL engines will fly on *Alphabus*, the new European GEO platform to be launched later this year, as well as on *BepiColombo*. The power for a Neptune mission EP system would be provided by solar arrays. With current technology, the specific power provided is 75 W/kg at 1 AU (*Dawn* for instance achieved 82 W/kg at 1 AU). The total 1 AU power output of the envisaged Neptune SEP module solar arrays would be similar to that of *Alphabus*. An estimate of the total mass of an SEP module for a Neptune orbiter is 1,500 kg, including solar arrays, tanks, structure, and 640 kg of propellant. A Neptune orbiter SEP module would not be subject to degradation at high temperatures, unlike the *BepiColombo* SEP module. Although not favoured here, we note that the lower TRL alternative options of an E-sail [Janhunen et al., 2013] and aerocapture at NOI have potential to become more attractive options in future.

5.3 Preliminary Mission Analysis

A detailed Neptune orbiter mission analysis is beyond the scope of this white paper. However, even the high-level discussion of mission concepts presented here requires a preliminary mission analysis to be carried out, for reasons explained below. This preliminary analysis is intended to serve as a starting point for future, detailed analysis of an ESA L-class mission to Neptune and Triton. Full details of the results of our preliminary mission analysis (not given here due to length constraints) are available on request.

Interplanetary transfer to Neptune

Issues such as RTG lifetime (20 years, including pre-launch ground phase) make the duration of an interplanetary transfer to Neptune an essential aspect of any discussion of Neptune orbiter mission concepts. We investigated trajectory options involving a launch from Kourou centred on the 2028-2034 timeframe. Rather than project future Ariane launcher performance, we assume an Ariane 5 ECA launcher for this preliminary analysis. Interplanetary transfer to Neptune requires a Gravity Assist (GA) by either Jupiter or Saturn a few years after launch because of RTG lifetime and to mitigate propellant requirements. However, a Jupiter GA is more effective than a Saturn GA for a Neptune orbiter mission [Landau et al., 2009].

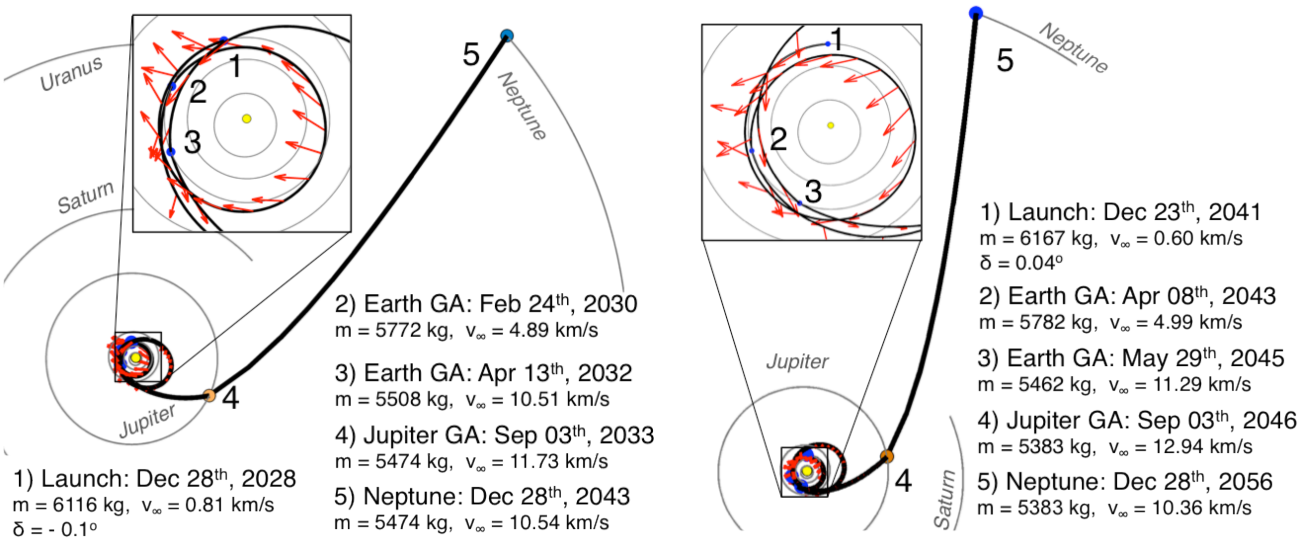

Figure 11. Example interplanetary transfer with launch in 2028 (left) and 2041 (right). Trajectory arcs where SEP is employed are modelled by small impulsive Delta-V (represented by red arrows).

Favourable opportunities for a Jupiter GA will exist in 2033 and in 2046 (separated by a Jupiter-Neptune synodic period of ~13 years). We thus studied interplanetary transfers that take advantage of each of these opportunities. One or more Earth GAs and orbital manoeuvres are required prior to the Jupiter GA in both cases, with mission-enabling SEP employed in this phase since chemical propulsion would require large amounts of fuel (>4 tons, neglecting use of low-TRL aerocapture for Neptune orbit insertion). Figure 11 shows an example interplanetary transfer for each Jupiter GA opportunity. Launch is in 2028 and Neptune arrival is in 2043 in the first example, and launch is in 2041 and Neptune arrival is in 2056 in the second example. The transfer duration is ~15 years in both examples. These transfer options deliver ~1,800 kg dry mass into Neptune orbit, in line with estimates provided by the past Neptune orbiter study by NASA [Marley et al., 2010], and similar to the JUICE dry mass of 1,800 kg (including radiation shielding not required at Neptune).

Neptune orbital tour

Another essential aspect of a Neptune orbiter mission concepts discussion is the question of whether a spacecraft tour would allow the necessary observation opportunities. The frequency and geometry of Triton flybys is crucial. The key point we would like to highlight is that Triton is an effective "tour engine", allowing a wide range of orbit trajectories and observation opportunities. We present one example Neptune tour here, which is essentially a proof of concept. Although not optimised, this tour would address all scientific questions. Our example tour is 2 years in duration, starting with interplanetary transfer arrival conditions given by the first stage of this preliminary analysis. At the beginning of the tour the spacecraft flies between the inner rings and executes NOI at 3,000 km altitude, following previous NASA mission concepts [Marley et al., 2010]. The tour is shown in Figure 12. In two years there are 55 Triton flybys, with groundtracks shown in Figure 13. Total chemical Delta-V for the whole mission is ~3 km/s, similar to *JUICE* (~2.6 km/s).

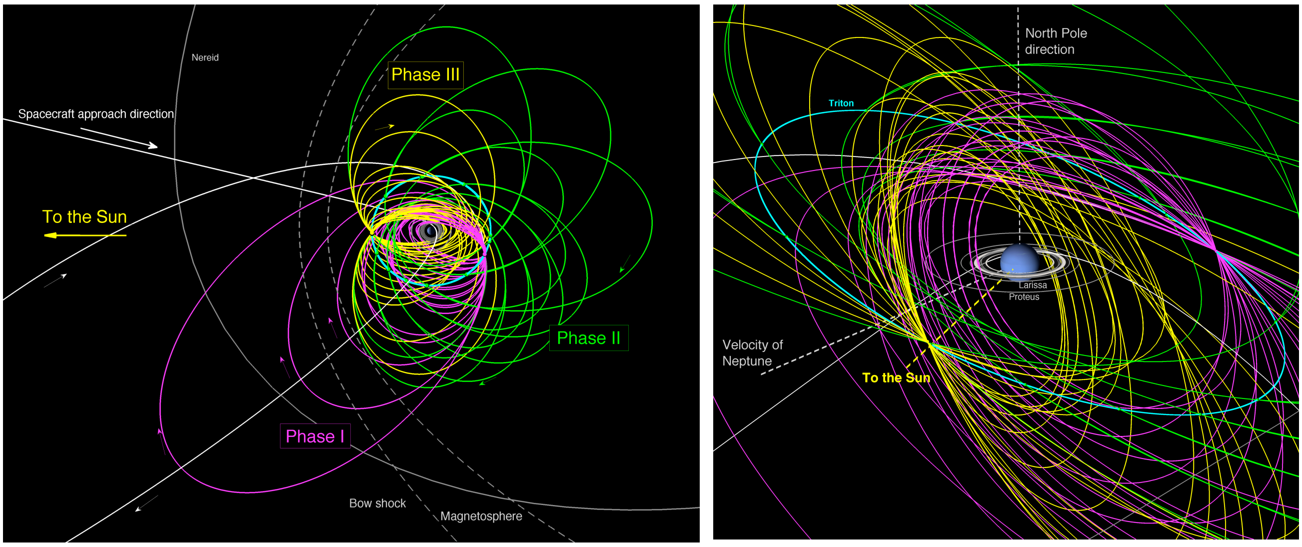

Figure 12. Example Neptune orbital tour. Left: Viewed from Neptune's north pole. Right: Close-up of the tour.

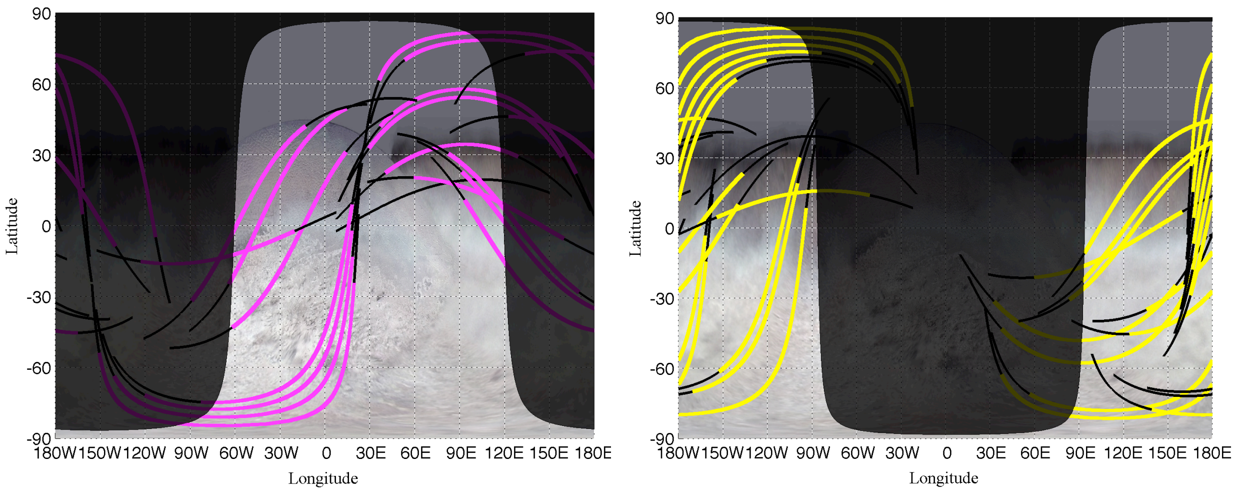

Figure 13. Groundtracks of Triton flybys during Phase I (left) and Phase III (right). Below 5000 km (black), below 1000 km (coloured).

During the three phases of this example tour there are inclined Neptune orbits and orbits in Triton's orbital plane. Triton flybys occur over the full range of Triton orbital locations, and at altitudes between ~150 and ~1,000 km. There is significant flexibility in, for example, Triton flyby altitudes, which can be raised or lowered as necessary. Our preliminary analysis suggests that a Triton orbit phase could be included at a Delta-V cost of ~300 m/s, using a transfer similar to that planned for *JUICE* [Campagnola et al., 2012]. Close flybys at Neptunian moons other than Triton are also possible.

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