



Neptune and Triton: Essential pieces of the Solar System puzzle

A. Masters, N. Achilleos, C.B. Agnor, S. Campagnola, S. Charnoz, B. Christophe, A.J. Coates, L.N. Fletcher, G.H. Jones, L. Lamy, et al.

► To cite this version:

A. Masters, N. Achilleos, C.B. Agnor, S. Campagnola, S. Charnoz, et al.. Neptune and Triton: Essential pieces of the Solar System puzzle. Planetary and Space Science, 2014, 104, pp.108-121. 10.1016/j.pss.2014.05.008 . hal-02547155

HAL Id: hal-02547155

<https://hal.science/hal-02547155>

Submitted on 1 Apr 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 Neptune and Triton: Essential pieces of the Solar System puzzle

2

3 A. Masters^a, N. Achilleos^{b,c}, C. B. Agnor^d, S. Campagnola^a, S. Charnoz^{e,f},
4 B. Christophe^g, A. J. Coates^{c,h}, L. N. Fletcherⁱ, G. H. Jones^{c,h}, L. Lamy^j, F. Marzari^k,
5 N. Nettelmann^l, J. Ruiz^m, R. Ambrosiⁿ, N. Andre^o, A. Bhardwaj^p, J. J. Fortney^l,
6 C. J. Hansen^q, R. Helled^f, G. Moragas-Klostermeyer^s, G. Orton^t, L. Ray^{b,c}, S.
7 Reynaud^u, N. Sergis^v, R. Srama^s, M. Volwerk^w.

8

9 ^aInstitute of Space and Astronautical Science, Japan Aerospace Exploration Agency,
10 3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa 252-5210, Japan.

11 ^bAtmospheric Physics Laboratory, Department of Physics and Astronomy, University
12 College London, Gower Street, WC1E 6BT, UK.

13 ^cThe Centre for Planetary Sciences at UCL/Birkbeck, Gower St., London, WC1E
14 6BT, UK.

15 ^dAstronomy Unit, School of Physics and Astronomy, Queen Mary University of
16 London, Mile End Road, London, E1 4NS, UK.

17 ^eLaboratoire AIM, Université Paris Diderot/CEA/CNRS, 91191 Gif-sur-Yvette
18 Cedex, France.

19 ^fInstitut Universitaire de France, 103 Blvd. Saint Michel, 75005 Paris, France.

20 ^gONERA - The French Aerospace Lab, 92322 Châtillon, France.

21 ^hMullard Space Science Laboratory, Department of Space and Climate Physics,
22 University College London, Holmbury St. Mary, Dorking, Surrey, RH5 6NT, UK.

23 ⁱAtmospheric, Oceanic & Planetary Physics, Clarendon Laboratory, University of
24 Oxford, Parks Road, OX1 3PU, UK.

25 ^jLESIA, Observatoire de Paris, CNRS, Université Pierre et Marie Curie, Université
26 Paris Diderot, Meudon, France.

27 ^kDipartimento di Fisica, Università di Padova, Via Marzolo 8, 35131 Padova, Italy.

28 ^lDepartment of Astronomy and Astrophysics, University of California, Santa Cruz,
29 CA 95064, USA.

30 ^mDepartamento de Geodinámica, Facultad de Ciencias Geológicas, Universidad
31 Complutense de Madrid, 28040 Madrid, Spain.

32 ⁿDepartment of Physics and Astronomy, University of Leicester, University Road,
33 Leicester, LE1 7RH, UK.

34 ^oIRAP, CNRS, Univ. Paul Sabatier Toulouse, Toulouse, France.

35 ^pSpace Physics Laboratory, Vikram Sarabhai Space Centre, Trivandrum 695022,
36 India.

37 ^qPlanetary Science Institute, Tucson, AZ 85719, USA.

38 ^rDepartment of Geophysics and Planetary Science, Tel Aviv University, Tel Aviv
39 69978, Israel.

40 ^sInstitut für Raumfahrtssysteme, Universität Stuttgart, Pfaffenwaldring 31, 70569
41 Stuttgart, Germany.

42 ^tMS 169-237, Jet Propulsion Laboratory, California Institute of Technology, 4800
43 Oak Grove Drive, Pasadena, CA 91109, USA.

44 ^uLaboratoire Kastler Brossel (LKB), ENS, UPMC, CNRS, Campus Jussieu, F-75252
45 Paris Cedex 05, France.

46 ^vOffice of Space Research and Technology, Academy of Athens, Soranou Efessiou 4,
47 1527 Athens, Greece.

48 ^wSpace Research Institute, Austrian Academy of Sciences, Schmiedlstraße 6, 8042
49 Graz, Austria.

50

51 Corresponding author: A. Masters

52 Corresponding author email: a.masters@stp.isas.jaxa.jp

53

Abstract

The planet Neptune and its largest moon Triton hold the keys to major advances across multiple fields of Solar System science. The ice giant Neptune played a unique and important role in the process of Solar System formation, has the most meteorologically active atmosphere in the Solar System (despite its great distance from the Sun), and may be the best Solar System analogue of the dominant class of exoplanets detected to date. Neptune's 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. Triton is geologically active, has a tenuous nitrogen atmosphere, and is predicted to have a subsurface ocean. However, our exploration of the Neptune system remains limited to a single spacecraft flyby, made by *Voyager 2* in 1989. Here, we present the high-level science case for further exploration of this outermost planetary system, based on a white paper submitted to the European Space Agency (ESA) for the definition of the second and third large missions in the ESA Cosmic Vision Programme 2015-2025. We discuss all the major science themes that are relevant for further spacecraft exploration of the Neptune system, and identify key scientific questions in each area. We present an overview of the results of a European-led Neptune orbiter mission analysis. Such a mission has significant scope for international collaboration, and is essential to achieve our aim of understanding how the Solar System formed, and how it works today.

Keywords: Neptune, Triton

1. Introduction

The primary aim of this paper is to review what we currently know about the Neptune planetary system, and to highlight the many fundamental scientific questions that remain unanswered. This review is based on a white paper that was submitted to the European Space Agency (ESA) in May 2013, to inform the selection of the science themes that will be addressed by the second and third large missions in the ESA Cosmic Vision Programme 2015-2025.

Neptune is classified as one of the gas giant planets, along with Jupiter, Saturn, and Uranus, and additionally forms a subgroup with Uranus called the “ice giants”, because both planets are 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. The Neptune system is unique, providing opportunities for major advances across multiple scientific fields that cannot be made in any other planetary environment.

Neptune orbits the Sun at a distance ~ 30 times greater than the mean Sun-Earth distance (an Astronomical Unit, AU). A Neptune day is just over 16 hours long, and a planetary obliquity of $\sim 30^\circ$ leads to seasons over Neptune’s ~ 165 -year orbit. 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 (Stone and Miner, 1989). Figure 1 shows *Voyager 2* imaging of Neptune during approach to the planet (Smith et al., 1989). The combination of this brief encounter and ground-based and space-based 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 (see the review by Cruikshank (1995)). The Neptune system is barely explored compared to other planetary systems, and never with modern spacecraft instrumentation.

Sections 2 and 3 of this paper are dedicated to outlining the current state of knowledge, and defining key scientific questions, concerning the planet Neptune and its moon Triton, respectively. Each sub-section deals with one of the various science themes of Neptune/Triton science. We propose that the host of open questions put forward in Sections 2 and 3 make further spacecraft exploration of the Neptune system a priority for future Solar System exploration. Thus, in Section 4 we define further science questions that could be addressed by a spacecraft bound for the outermost planet. Finally, in Section 5 we present an overview of a recent European-led Neptune orbiter mission analysis.

2. Neptune

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 (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, interacting with the planets via 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.

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 improvement of planetary formation theories, 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, where, 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). While Uranus appears to have been radically altered by collisional processes, producing low internal heat flux, Neptune appears to have only been subject to scattering processes and is therefore expected to be more typical of these exoplanets of similar size, possibly sharing a similar evolution. 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?
- Are Neptune-sized exoplanets "ice giants"?

2.2. Interior

Although difficult to directly access through observations, the interior of Neptune holds unique information about the early Solar System and on the formation, structure, and composition of ice giant planets in general. Fortunately, the properties of Neptune's interior are mapped onto the observable gravity field, the magnetic field, the lower atmosphere, and the measurable luminosity. Therefore, a combination of new and more accurate observations and development of consistent interior models would allow us to solve a number of major mysteries concerning planetary atmospheres, formation, and evolution. In particular, why is Neptune's measured intrinsic heat flux so high? This high intrinsic heat flux represents an important difference between Neptune and Uranus, which may be due to different formation and evolution histories of the two ice giants.

The *Voyager 2* encounter with Neptune provided us with some constraints on Neptune's interior. Prior to the encounter, Neptune 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). Our current, still very limited, understanding of Neptune's interior is illustrated in Figure 3.

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 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 a rock-rich deep interior.

The key questions of the abundance and metallization of hydrogen in Neptune's deep interior, and the degree to which its interior is convective and adiabatic, are central to understanding how Neptune generates its magnetic field (see Section 2.5). Both a dynamo in a thin, ionic water shell above a stably stratified interior, and a large, metallic core dynamo have been suggested to explain the Voyager planetary magnetic field measurements. However, stable stratification over a large fraction of Neptune's interior challenges explanations for the observed high luminosity.

The fraction of heavy elements in the outer envelope of Neptune's interior is also unclear, and is related to the chemistry and composition of the tropospheric layer of Neptune's atmosphere (see Section 2.3). While adiabatic Neptune interior models allow for a reasonable deuterium enrichment in the ices, similar to that of ocean water or cometary ices (see Figure 3a), the atmospheric oxygen abundance from adiabatic interior models does not exceed $\sim 200\times$ protosolar, in contrast to the O:H enrichment as inferred from atmosphere models ($\sim 500\times$ protosolar) that are adjusted to explain the measured tropospheric CO enrichment (Luszcz-Cook and de Pater 2013) (see Figure 3b).

Key scientific questions:

- Why is the heat flux from Neptune's interior so high?
- Is the magnetic field generated in a thin shell or in a metallic, convective interior?
- What is the origin and abundance of light elements in the deep interior, and of ices in the atmosphere and outer envelope?

2.3. Atmosphere

Despite its distance from the Sun, Neptune displays some of the most dramatic meteorological and chemical activity of any atmosphere in our Solar System, displaying zonal banding, dark ovals and sporadic clouds, along with the fastest wind speeds measured in any planetary atmosphere (up to 450 m/s, compared with 30-100 m/s on Earth (Hammel et al., 1989; Ingersoll et al., 1990; Sromovsky et al., 2001)). Discrete cloud features, potentially comprising ices of methane and ammonia, have been observed in the visible and near-infrared, ranging from the main cloud deck at 2-3 bars up to altitudes above the tropopause at 100 mbar (e.g. Smith et al., 1989; Karkoschka, 2011; Irwin et al., 2011). Powerful zonal winds and strong latitudinal variations lead to significant shears, tearing clouds apart on timescales of hours, as shown in Figure 4.

Given that the solar input at Neptune is only a fraction of that received by Jupiter, this strong atmospheric activity may be driven by a huge reservoir of internal heat left over from the planet's formation (see Section 2.2). Indeed, Neptune's 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 and Conrath, 1991), and in stark contrast with Uranus' apparently negligible internal heat flux.

Neptune provides an important test for models balancing seasonally dependent insolation (due to the 28° axial tilt and the 165-year orbit) and excess internal heat flux. Neptune has a different relation between banded cloud structures, atmospheric temperatures and zonal wind structure than Jupiter or Saturn. Rapidly evolving convective cloud activity seems to prevail at cool mid-latitudes (e.g. Fig. 4), and

ground-based observations have shown that clouds in the main storm band at 20-40°S have become increasingly vigorous in the two decades since the *Voyager 2* flyby (Lockwood and Jerzykiewicz, 2006; Hammel and Lockwood, 2007). Tropospheric zonal flow is characterized by strong retrograde flow at the warmer equator (e.g. Conrath et al., 1991) and a high-latitude prograde jet (e.g. Sromovsky et al., 2001) confining a seasonally variable polar vortex of unusually high temperatures and unique chemical composition (e.g. Orton et al., 2007, 2012). However, recent analysis of Neptune's gravitational field (Kaspi et al., 2013) suggests that this zonal velocity pattern is tightly confined to the outermost layers of Neptune, favouring a shallow meteorology. Dark ovals (e.g., the Great Dark Spot observed by *Voyager 2* (Smith et al., 1989)) are enormous vortices, sometimes associated with bright white orographic clouds at higher altitudes. Correlating visible changes to cloud albedo, winds, eddies and vortices with environmental changes (e.g., latent heat release from cloud condensation, long-term seasonal variability in temperature and composition) is essential to understand the processes controlling the changing face of Neptune.

Some of the basic dynamical, chemical, and cloud-forming processes at work within Neptune's churning atmosphere are unknown. Neptune's atmospheric composition is determined by condensation chemistry, vertical mixing, external influx of oxygenated species from infalling comets and dust (e.g. Lellouch et al., 2010a), and a rich hydrocarbon photochemistry due to the UV destruction of methane (e.g. Orton et al., 1987; Moses et al., 2005; Greathouse et al., 2011). Knowledge of elemental enrichments (C/H, N/H, O/H), isotopic ratios (D/H, $^{13}\text{C}/^{12}\text{C}$, $^{15}\text{N}/^{14}\text{N}$) and noble gas abundances (especially the He/H₂ ratio) would provide constraints on the delivery of these materials to the forming proto-Neptune, and early Solar System conditions. Furthermore, mapping the spatial distributions of cloud-forming volatiles,

disequilibrium species, and photochemical products would teach us about chemical processes and cloud formation at work within the ice giant, and their variability from equator to pole. The latitudinal distribution of methane (e.g. Karkoschka and Tomasko, 2011) would reveal whether it is enhanced by tropical uplift near the equator, mid-latitude convective activity, or by warming of the cold trap at the seasonally-heated poles (e.g. Orton et al., 2007). If Neptune's dynamics are analogous to those of Saturn, then its apparent polar heating would not only be the result of seasonal warming but also might contain a very compact region that is heated by a dynamically forced downdraft.

Key scientific questions:

- What drives the circulation and dynamics of the most meteorologically active atmosphere in our Solar System?
- What is the composition and structure of Neptune's atmosphere?
- What is the nature of atmospheric chemistry and cloud formation on an ice giant?
- What is the atmospheric structure and cloud properties from the troposphere to the thermosphere?

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).

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

327 seem to orbit inside Neptune's Roche limit for ice, which implies that the small
328 moons may be denser than ice (Tiscareno et al., 2013). Tidal disruption of the weakest
329 moons could give birth to narrow rings (Leinhardt et al., 2012). Neptune's regular
330 satellites are barely characterised, and their mass and densities are simply inferred
331 from model-dependent arguments concerning the evolution of the rings. The surface
332 of Proteus, the largest of Neptune's inner satellites, appears to be densely cratered,
333 and its non-hydrostatic shape may be the signature of past collisions, as illustrated by
334 its large crater Pharos. The surfaces of the four innermost moons have never been
335 imaged, representing a serious gap in our knowledge of the Neptune planetary system.

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

343 Each of the Solar System's giant planets is known to possess distant irregular
344 satellites on eccentric, prograde and retrograde orbits. In addition to 340-km Nereid,
345 Neptune has at least six irregular satellites larger than about 40-km in size (Holman et
346 al., 2004). These rogue satellites are likely to be the last objects permanently captured
347 by Neptune, with their origin and evolution tightly coupled to Neptune's orbital
348 migration and Triton's tidal and collisional evolution. Like Triton, these captured
349 primitive bodies may have originated in the Kuiper Belt, and could provide us with
350 important information about Neptune's history, the collisional processing of captured
351 satellites, and the provenance and evolution of Kuiper Belt Objects (KBOs).

352

353 Key scientific questions:

- 354 • Why is the composition of Neptune's rings different to that of any other planetary
355 ring system, and how do the ring arcs survive?
- 356 • Does Neptune have extended, dusty rings like Jupiter and Saturn?
- 357 • How did Neptune's inner satellites form, and how does the coupled ring-moon
358 system work?
- 359 • Are Nereid and the other irregular satellites captured KBOs?

360

361 2.5. Magnetic environment

362

363 Neptune's magnetic field has a complex geometry. The single *Voyager 2* flyby
364 provided us with a limited understanding of the field structure, which nevertheless
365 revealed a large angle of $\sim 47^\circ$ between the magnetic dipole and rotation axes of the
366 planet, a dipole centre significantly offset from the centre of the planet by ~ 0.5
367 Neptune radii (R_N), and appreciable non-dipolar components (Ness et al., 1989;
368 Connerney et al., 1991; Holme and Bloxham, 1996). The origin of such an unusual
369 field is unclear, partly because of the lack of concrete knowledge about the planetary
370 interior (see Section 2.2). Solving the problem of how Neptune generates its magnetic
371 field is a major challenge for dynamo theorists, with broad implications for the field
372 of planetary magnetism (e.g. Stanley and Bloxham, 2004; Soderlund et al., 2013).

373 The nature of Neptune's magnetic field leads to a highly irregular
374 magnetosphere surrounding the planet (Bagenal, 1992). The competition between the
375 pressure exerted by the flow of solar wind plasma from the Sun and the pressure
376 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 changes in the magnetosphere in only half a planetary rotation period (~ 8 hrs), passing successively from an Earth-like to a pole-on configuration (magnetic axis parallel to the solar wind flow) every half a rotation, as illustrated in Figure 6.

There are numerous important questions about how Neptune's magnetosphere works, which are highly relevant for understanding how it interacts with the planetary atmosphere, rings, and satellites. Uncertainty surrounds the question of how the magnetosphere changes so dramatically, and what this means for the coupling between various parts of the system. This dynamic nature makes Neptune's magnetosphere an excellent Solar System laboratory for studying charge separation and equilibration due to highly variable magnetic fields, and the timescales associated with the main regimes of plasma transport (convection, corotation) and different particle acceleration mechanisms.

The relative importance of sources and sinks of plasma in Neptune's magnetosphere is also unknown (Belcher et al., 1989; Gurnett et al., 1989; Krimigis et al., 1989; Stone et al., 1989). Triton is thought to be an important source (Richardson et al., 1991) (see Section 3), as well as charged dust particles harboured by the planet's rings. 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 such 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).

402 Auroral radio emission with a rich variety of components (smoothed, bursty)
403 has been unambiguously identified (e.g. Zarka et al., 1995). Such emissions appear to
404 be unique to the ice giants, and are therefore among the most mysterious in the Solar
405 System, and essential for understanding Neptune's magnetospheric system and the
406 atmospheric energy budget. In addition, H₂ auroral emissions have been tentatively
407 identified in the UV (Bhardwaj and Gladstone, 2000). As the furthest planet from the
408 Sun (i.e. experiencing the lowest dynamic pressure) with a highly variable angle
409 between the magnetic axis and the solar wind flow, how Neptune's dynamic
410 magnetosphere interacts with the solar wind is of great interest (e.g. Schulz et al.,
411 1995). The planetary bow shock wave that stands upstream of the magnetosphere in
412 the solar wind flow is expected to be the strongest (highest Mach number) in the
413 heliosphere, and the interplanetary (solar) magnetic field is very weak (~0.2 nT). As a
414 result, the magnetopause boundary of Neptune's magnetosphere is a unique
415 laboratory in which to study fundamental processes like magnetic reconnection,
416 particularly in terms of plasma β (e.g. Masters et al., 2012).

417

418 Key scientific questions:

- 419 • What is the origin and structure of Neptune's complex magnetic field?
- 420 • How does the magnetosphere re-configure on such short timescales?
- 421 • What are the sources and sinks of magnetospheric plasma?
- 422 • How are Neptune's auroral emissions generated (including radio), and does this
423 differ from the emissions observed at the Earth, Jupiter, and Saturn?
- 424 • How does Neptune's magnetosphere interact with the solar wind?

425

426 3. Triton

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 and 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.

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 KBO.

Triton's capture must have left it on an orbit that was much larger (orbital radius: $\sim 80\text{--}1,000 R_N$) and more eccentric (eccentricity: $>\sim 0.95$) 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 and Charnoz, 2012) (see Section 2.4). In either case, the inner satellite system has experienced extreme collisional processing. Neptune's distant irregular satellites exterior to Triton 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 ($\sim > 20\%$) from the debris disk (Cuk and Gladman, 2005). The accretion of this material would have hastened Triton's orbital decay, and rendered it a composite of heliocentric and planetocentric material. Triton's orbital decay was ultimately 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:

- What physical memory does Triton retain of its heliocentric 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 includes a relatively high mean density (2.065 g cm^{-3}), implying 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 and Kirk, 2007).

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, 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 and McKinnon, 2000; Schenk and Zahnle, 2007). Triton's surface is therefore one of the younger surfaces in the Solar System, strongly suggesting that Triton is currently a geologically active satellite.

Triton's surface shows a variety of terrains very different to those in other icy satellites. 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. This kind of terrain has been interpreted to have been formed through compositional diapirism affecting a ~20 km thick crustal layer (Schenk and Jackson, 1993). The other terrain type consists of undulating or smooth plains that show a variety of landforms, including terraces, and depressions filled with smooth materials and “ice lakes”. The transition between both terrain types is characterized by the progressive flooding and disappearance of the cantaloupe texture, suggestive of onlapping by smooth materials emplacement.

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.

The brittle lithosphere (the outermost rigid layer of Triton) 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. Indeed, tidal heating should be comparatively reduced in the current orbital eccentricity (Gaeman et al., 2013).

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). These plumes are interpreted to be consequence of geyser-like activity, which could be powered by insulation-driven heating of the nitrogen cap (Soderblom et al., 1990). However, an endogen origin (driven by internal heat) cannot be currently

discarded; this possibility would be consistent with fast ejection speed suggesting a deep source (Laufer et al., 2013). Numerous dark streaks present on the polar cap may also be a result of such plume activity.

Key scientific questions:

- What is 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 through 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 CH₄, 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., 2010b).

551 A profile of Triton's atmosphere is shown in Figure 9. Surface atmospheric
552 pressure is thought to be $\sim 1.4\text{--}1.9$ Pa ($14\text{--}19$ μ bar) (Broadfoot et al., 1989, Tyler et al.,
553 1989). Pressure equilibrium in the nitrogen-rich atmosphere implies an upper limit for
554 the surface temperature of Triton of ~ 38 K. Triton's atmosphere is seasonally
555 variable, as the CH_4 abundance observed recently was several times that observed by
556 *Voyager* (Lellouch et al., 2010b).

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

569

570 Key scientific questions:

- 571 • What molecular species are present in Triton's atmosphere?
- 572 • What is the distribution and source of aerosols in the atmosphere?
- 573 • How do winds affect the structure of Triton's atmosphere?
- 574 • What are the properties of the nitrogen plumes?
- 575 • What is the rate of dust infall to Triton's atmosphere?

3.4. Interaction with Neptune's 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 $\sim 340\text{km}$, as determined by radio science observations. One surprise revealed by these data was the observed high ionospheric density of $\sim 46,000\text{ cm}^{-3}$ (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 ($>10\text{ keV}$) precipitating particles from Neptune's magnetosphere (Strobel et al., 1990). The measured energy flux of $>22\text{keV}$ 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.

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 $\gg 40 R_N$ (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 km s^{-1}) and the expected local speed of magnetospheric plasma flow ($\sim 40 \text{ km s}^{-1}$) 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 magnetic fields at Triton (e.g. due to a subsurface ocean) 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 and 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 cruise to Neptune

In Sections 2 and 3 we have presented the major themes of Neptune and Triton science, identifying key scientific questions. We propose that this host of open questions make further spacecraft exploration of the Neptune system a priority for future Solar System exploration. Motivated by this, in this section we discuss the further science themes where important open questions could be addressed by a spacecraft bound for the outermost planet.

Small bodies of the outer Solar System. A spacecraft on an interplanetary cruise phase to Neptune would provide us with an excellent opportunity to characterize small bodies of the outer Solar System, with significant scientific gains. Encounters with small bodies during cruise phases have provided a wealth of data from several missions, including *Galileo* when travelling to Jupiter, and *NEAR Shoemaker* en route to its primary target Eros.

Apart from the moons of the outer planets, no minor planetary bodies have so far been encountered beyond the asteroid belt. Between 5 and 30 AU from the Sun, most small bodies fall into the category of Centaurs. This region is one where orbital lifetimes are typically $<10^7$ years (Holman and Wisdom 1993). The unstable nature of orbits in this region implies that rather than being bodies formed *in situ* beyond the orbit of Jupiter, most Centaurs in fact originate from the Kuiper Belt, i.e. further from the Sun, with an admixture of objects from even further afield: the Oort Cloud.

Given the expected higher volatile content of these outer Solar System small bodies compared to the typical makeup of such objects residing closer to the Sun, scientific observations in the vicinity of such bodies beyond the orbit of Jupiter would strongly complement the data gathered *in situ* on more volatile-poor asteroids closer

676 to the Sun. There is a strong possibility of many of these objects being active today,
677 such as the first Centaur found: 2060 Chiron, and 174P/Echeclus (Bauer et al. 2008).
678 As well as the surveying of the bodies by remote sensing instruments, to characterize
679 the surface composition and morphology, and to search for activity, particle and fields
680 instruments should also be employed to detect the effects of any current activity on
681 these bodies, and to search for signs of remnant magnetism.

682 *Interplanetary and interstellar dust.* Our Solar System is pervaded by dust,
683 both interplanetary and interstellar. However, the distribution of this dust is not well
684 known. Revealing the properties of this dust from 1 to 30 AU would have
685 implications for Solar System formation and evolution (see Section 2.1), providing
686 information about the Kuiper Belt. Interstellar dust grains are of particular interest as
687 they are expected to preserve the conditions of star formation (Altobelli et al., 2003).
688 In addition, there is potential for a comet flyby, or a crossing of a comet trail, during a
689 cruise to the Neptune system. Dust measurements made during such encounters would
690 also provide a link to the properties of the Oort cloud, and/or distant KBOs.

691 *Heliospheric physics.* The continuous flow of solar wind plasma away from
692 the Sun leads to significant energy flux through our entire Solar System, and this
693 plasma flow eventually encounters its heliopause boundary. However, very few solar
694 wind measurements have been made in the outer Solar System, beyond 10 AU. How
695 solar wind structures (e.g. coronal mass ejections), evolve from the Sun to Neptune is
696 therefore a largely open question in heliospheric physics. In addition, Energetic
697 Neutral Atoms (ENAs) have never been detected in the distant Solar System where
698 Neptune resides, and would shed light on the global structure of the heliosphere itself.
699 The power of ENA imaging for resolving outer heliospheric structure has been

demonstrated by missions like *IBEX* and *Cassini*, and provides a valuable global context for *in situ Voyager* observations sent back from the edge of the Solar System.

Fundamental Physics: Testing General relativity. 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 and 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 closely 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:

- What are the characteristics of the Centaurs in the outer Solar System?
- How many of these Centaurs are active?
- 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 orbiter mission analysis

As introduced in Section 1, this review of Neptune-Triton science is based on a white paper that was submitted to ESA to inform the selection of the science themes that will be addressed by the second and third large missions in the ESA Cosmic Vision Programme 2015-2025. While a full discussion of the Neptune orbiter mission concept that was presented in the white paper is beyond the scope of this paper (and will be presented in a future, dedicated publication), here we give a brief overview.

Mission analysis heritage is provided by the most recent NASA Jet Propulsion Laboratory (JPL) mission concept study (Marley et al., 2010), the JPL-led *Argo* mission concept (Hansen et al., 2010a, b; Spilker et al., 2010), and the *Outer Solar System Mission* submitted to ESA in response to the most recent call for M-class mission proposals (Christophe et al., 2012). There is significant scope for international collaboration, and potential to use ESA *JUICE* mission hardware in a Neptune mission (Dougherty et al., 2011), but with far lower radiation shielding requirements.

We have identified three enabling technologies for an ESA-led Neptune orbiter mission:

1. *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 performed 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.

2. 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., 2012). The radioisotope chosen for the European space nuclear power program is Americium-241 (Sarsfield et al., 2013, O'Brien et al. 2008) which has a longer half-life (433 years) when compared to Plutonium-238 (88 years); however, Plutonium-238 has been used in RTG systems for more than half a century. The current European RTG lifetime requirement is 20 years. Given that americium has a half-life, which is much longer than any nominal mission lifetime, isotope decay will not be a limiting factor. Considering that historically spacecraft powered by RTG systems have exceeded their nominal mission lifetimes, for example, Pioneer 10 exceeded its nominal 2 year mission by several decades (Dyal 1990) and Voyager 1 is still transmitting data. Extended lifetime testing of European RTG and SRG solutions will reduce any uncertainties in lifetime values; however, this type of activity will be part of future studies. US ASRG designed for at least 17-year mission life (NASA, 2013) are currently undergoing extended lifetime testing (NASA, 2012). If we take the nominal power requirement of a Neptune orbiter mission to be 500 W, 10 European RTGs or 5 SRGs would be sufficient, producing a total electric power of 500 W. In the case of RTGs the mass would be of order 250 kg, assuming 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., 2012). Assuming a 20% maturity margin, the total mass would be ~300 kg. Specific power values for European SRG solutions will be determined as at the end of a current ESA study. SRG solutions for a mission to the outer planets after 2028 should not be excluded at this stage and should form part of future more detailed mission trade-off studies.

799 3. *Solar Electric Propulsion (SEP)*. An RTG lifetime comparable to the interplanetary
800 transfer time leads to a third enabling technology for a Neptune orbiter mission.
801 Options to reduce the interplanetary transfer time are an SEP module, an Electric Sail
802 (E-sail) (Janhunen et al., 2013), and aerocapture at NOI. The option with the highest
803 TRL is SEP, which would provide large Delta-V with small propellant mass in the
804 earlier part of an interplanetary transfer to Neptune, before module ejection prior to
805 NOI. An SEP module with four QinetiQ T6 Gridded Ion Engines (3 nominal and 1
806 redundant) would be sufficient, each providing 155 mN of thrust and requiring 5.5
807 kW. These high-TRL engines will fly on *Alphabus*, the new European GEO platform
808 to be launched later this year, as well as on *BepiColombo*. The power for a Neptune
809 mission EP system would be provided by solar arrays (total 1 AU power output
810 similar to *Alphabus*) (specific power of 75 W/kg at 1 AU, compared to 82 W/kg for
811 *Dawn*). An estimate of the total mass of an SEP module for a Neptune orbiter is 1,500
812 kg, including solar arrays, tanks, structure, and 640 kg of propellant. A Neptune
813 orbiter SEP module would not be subject to degradation at high temperatures, unlike
814 the *BepiColombo* SEP module.

815
816 An overview of our recent analysis of an ESA-led Neptune orbiter is given in
817 Table 1, and the interplanetary transfer and orbital tour are shown in Figure 11. This
818 is only one possible mission profile that places a spacecraft in orbit around Neptune,
819 which makes multiple flybys of Triton. In this example, launch is in 2028 from
820 Kourou, and the 15-year interplanetary cruise involves two Earth gravity assists and a
821 single Jupiter gravity assist. Following Neptune Orbit Insertion (NOI) in 2043, the
822 nominal orbital tour last for 2 years and includes 55 Triton flybys.

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). Favourable opportunities for a Jupiter GA will exist in 2033 and in 2046 (separated by a Jupiter-Neptune synodic period of ~ 13 years). This example takes advantage of the 2033 Jupiter GA opportunity. A mission-enabling SEP module is employed early in the transfer (see Figure 11), but the module is ejected prior to the Jupiter GA.

Regarding the Neptune orbital tour, we would like to highlight that Triton is an effective “tour engine”, allowing a wide range of orbit trajectories and observation opportunities. Our example tour is 2 years in duration, starting with interplanetary transfer arrival conditions given by the first stage of this mission 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). During the three phases of this example tour there are inclined Neptune orbits, orbits in Triton’s orbital plane, and 55 Triton flybys that cover the full range of Triton orbital locations, and altitudes between ~ 150 and $\sim 1,000$ 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.

The payload mass of ~ 70 kg would be split between a number of scientific instruments, including (but not limited to) a narrow-angle camera, a wide-angle camera, an infrared imager, an ultraviolet imaging spectrometer, an accelerometer, a

848 radio science experiment (including an ultrastable oscillator), a magnetometer, a
849 thermal imager, a range of particle detectors, a radio and plasma wave system, an
850 ENA camera, and a dust analyser. If equipped with a payload similar to that flown on
851 *Cassini* and other planetary orbiters, a Neptune orbiter would address all the Neptune-
852 Triton science themes described in Sections 2, 3, and 4.

853

854

855 Acknowledgements

856

857 We are very grateful to more than 100 scientists around the world who supported the
858 white paper on Neptune-Triton science that was submitted to ESA in May 2013 for
859 the definition of the second and third large missions in the Cosmic Vision Programme
860 2015-2025. AM and SC acknowledge the support of the JAXA International Top
861 Young Fellowship Programme.

862

863

864 Reference list

865

866 Ade, P.A.R., et al., 2013. Planck 2013 results. XVI. Cosmological parameters.

867 arXiv:1303.5076.

868

869 Adelberger, E.G., Gundlach, J.H., Heckel, B.R., Hoedl, S., Schlamminger, S., 2009.

870 Torsion balance experiments: A low-energy frontier of particle physics. Progress in

871 Particle and Nuclear Physics. 62, 102-134.

872

873 Agnor, C.B., Hamilton, D.P., 2006. Neptune's capture of its moon Triton in a binary-

874 planet gravitational encounter. Nature, 441, 192-194.

875

876 Altobelli, N., Kempf, S., Landgraf, M., Srama, R., Dikarev, V., Krüger, H., Moragas-

877 Klostermeyer, G., Grün, E., 2003. Cassini between Venus and Earth: Detection of

878 interstellar dust. J. Geophys. Res., 108, A10, doi:10.1029/2003JA009874.

879

880 Ambrosi, R.M, Williams H.R., Samara-Ratna P., Jorden, A., Slade, R., M., Jaegle,

881 M., Koenig, J., Bannister, N.P., Deacon, T., Stuttard, M., Crawford, E.A., Vernon, D.,

882 2012. Thermoelectric Converter System for Small-Scale RTGs, ESA TRP Report,

883 TECS-RTG-TR-D8-001-UL.

884

885 Bagenal, F., 1992. Giant Planet Magnetospheres, Ann. Rev. Earth Planet. Sci. 20,

886 289-328.

887

888 Bauer, J.M., Choi, Y.-J., Weissman, P.R., Stansberry, J.A., Fernández, Y.R.,
 889 Roe, H.G., Buratti, B.J., Sung, H.-I., 2008. The large-grained dust coma of
 890 174P/Echeclus, *The Publications of the Astronomical Society of the Pacific*, 120, 393-
 891 404.
 892
 893 Belcher, J.W., Bridge, H.S., Coppi, B., Gordon, G.S., Jr., Lazarus, A.J., McNutt, R.L.,
 894 Jr., Bagenal, F., Divers, O., Eviatar, A., Ogilvie, K.W., 1989. Plasma observations
 895 near Neptune - Initial results from Voyager 2. *Science* 246, 1478-1483.
 896
 897 Bhardwaj, A., Gladstone, G.R., 2000. Auroral emissions of the giant planets. *Rev.*
 898 *Geophys.* 38, 295-354.
 899
 900 Broadfoot, A.L., Atreya, S.K., Bertaux, J.L., Blamont, J.E., Dessler, A.J., Donahue, T.
 901 M., Forrester, W.T., Hall, D.T., Herbert, F., Holberg, J.B., Hunten, D.M.,
 902 Krasnopolsky, V.A., Linick, S., Lunine, J.I., McConnell, J.C., Moos, H.W.,
 903 Sandel, B.R., Schneider, N.M., Shemansky, D.E., Smith, G.R., Strobel, D.F.,
 904 Yelle, R.V., 1989. Ultraviolet spectrometer observations of Neptune and Triton.
 905 *Science*. 246, 1459-1466.
 906
 907 Campagnola, S., et al., 2012. Tisserand-leveraging transfers, *Advances in the*
 908 *Astronautical Sciences*. 143, 1205.
 909
 910 Christophe, B., et al., 2012. OSS (Outer Solar System): A fundamental and planetary
 911 physics mission to Neptune, Triton and the Kuiper Belt. *Exp. Astron.* 34, 203.
 912

913 Colwell, J.E., Esposito, L.W., 1990. A numerical model of the Uranian dust rings.
 914 Icarus 86, 530-560.
 915
 916 Connerney, J.E.P., Acuna, M.H., Ness, N. F., 1991. The magnetic field of Neptune. J.
 917 Geophys. Res. 96, 19023-19042.
 918
 919 Conrath, B.J., Flasar, F.M., Gierasch, P.J., 1991. Thermal structure and dynamics of
 920 Neptune's atmosphere from Voyager measurements. J. Geophys. Res. 96, 18931-
 921 18939.
 922
 923 Copeland, E.J., Sami, M., Tsujikawa, S., 2006. Dynamics of dark energy. Int. J. Mod.
 924 Phys. 15, 1753-1935.
 925
 926 Crida, A., Charnoz, S., 2012. Formation of regular satellites from ancient massive
 927 rings in the Solar System. Science 338, 1196.
 928
 929 Croft, S.K., Kargel, J.S., Kirk, R.L., Moore, J.M., Schenk, P.M., Strom, R.G., 1995.
 930 The geology of Triton, in: Cruikshank (Ed.), Neptune and Triton, Univ. of Arizona
 931 Press, Tucson, pp. 879-947.
 932
 933 Cruikshank, D.P. (Ed.), 1995. Neptune and Triton. Univ. of Arizona Press, Tucson.
 934
 935 Cuk, M., Gladman, B.J., 2005. Constraints on the orbital evolution of Triton. Ap. J.
 936 626, L113.
 937

938 Dougherty, M. K., et al., 2011. JUICE, Exploring the emergence of habitable worlds
 939 around gas giants. Assessment Study Report, European Space Agency,
 940 ESA/SRE(2011)18.
 941
 942 Dyal, P., 1990. Pioneers 10 and 11 Deep Space Missions, COSPAR Colloquia Series,
 943 1, 373-382.
 944
 945 Fressin, F., Torres, G., Charbonneau, D., Bryson, S. T., Christiansen, J.,
 946 Dressing, C.D., Jenkins, J.M., Walkowicz, L.M., Batalha, N.M., 2013. The false
 947 positive rate of Kepler and the occurrence of planets. *Ap. J.*, 766, 20.
 948
 949 Frieman, J.A., Turner, M.S., Huterer, D., 2008. Dark energy and the accelerating
 950 universe. *Annu. Rev. Astron. Astrophys.* 46, 385-432.
 951
 952 Gaeman, J., Hier-Majumder, S., Roberts, J.H, 2012. Sustainability of a subsurface
 953 ocean within Triton's interior. *Icarus* 220, 339-347.
 954
 955 Goldreich, P., Murray, N., Longaretti, P.Y., Banfield, D., 1989. Neptune's story.
 956 *Science* 245, 500-504.
 957
 958 Gomes, R., Levison, H.F., Tsiganis, K., Morbidelli, A., 2005. Origin of the
 959 cataclysmic Late Heavy Bombardment period of the terrestrial planets. *Nature* 435,
 960 466-469.
 961

962 Greathouse, T.K., Richter, M., Lacy, J., Moses, J., Orton, G., Encrenaz, T., Hammel,
 963 H.B., Jae, D., 2011. A spatially resolved high spectral resolution study of Neptune's
 964 stratosphere. *Icarus* 214, 606–621.
 965
 966 Gurnett, D.A., Kurth, W.S., Poynter, R.L., Granroth, L.J., Cairns, I.H., Macek, W.M.,
 967 Moses, S.L., Coroniti, F.V., Kennel, C.F., Barbosa, D.D., 1989. First plasma wave
 968 observations at Neptune. *Science* 246, 1494-1498.
 969
 970 Hammel, H.B., Beebe, R.F., de Jong, E.M., Hansen, C.J., Howell, C.D., Ingersoll,
 971 A.P., Johnson, T.V., Limaye, S.S., Magalhaes, J.A., Pollack, J.B., Sromovsky,
 972 L.A., Suomi, V.E., Swift, C.E., 1989. Neptune's wind speeds obtained by tracking
 973 clouds in Voyager images. *Science*. 245, 1367-1369.
 974
 975 Hammel, H.B., Lockwood, G.W., 2007. Long-term atmospheric variability on Uranus
 976 and Neptune. *Icarus* 186, 291–301.
 977
 978 Hansen, C., et al., 2010a. Neptune Science with Argo – A Voyage through the Outer
 979 Solar System. NASA Planetary Decadal Survey 2013-2022.
 980
 981 Hansen, C., et al., 2010b. Triton Science with Argo – A Voyage through the Outer
 982 Solar System. NASA Planetary Decadal Survey 2013-2022.
 983
 984 Holman, M. J., Wislomey, J. (1993), Dynamical stability in the outer solar system and
 985 the delivery of short period comets. *Astron. J.* 105, 1987-1999.
 986

987 Holman, M.J., Kavelaars, J.J., Grav, T., Gladman, B.J., Fraser, W.C.,
 988 Milisavljevic, D., Nicholson, P.D., Burns, J.A., Carruba, V., Petit, J.-M.,
 989 Rousselot, P., Mousis, O., Marsden, B.G., Jacobson, R.A., 2004. Discovery of five
 990 irregular moons of Neptune. *Nature* 430, 865-867.
 991
 992 Holme, R., Bloxham, J., 1996. The magnetic fields of Uranus and Neptune: Methods
 993 and models. *J. Geophys. Res.* 101, 2177-2200.
 994
 995 Hubbard, W.B., Podolak, M., Stevenson, D.J., 1995. The interior of Neptune. In:
 996 Cruikshank (Ed.), *Neptune and Triton*, Univ. of Arizona Press, Tucson, pp. 109-138.
 997
 998 Hussmann, H., et al., 2006. Subsurface oceans and deep interiors of medium-sized
 999 outer planet satellites and large trans-neptunian objects. *Icarus* 185, 258-273.
 1000
 1001 Ingersoll, A.P., 1990. Atmospheric Dynamics of the Outer Planets. *Science*. 248, 308-
 1002 315.
 1003
 1004 Irwin, P.G.J., Teanby, N.A., Davis, G.R., Fletcher, L.N., Orton, G.S., Tice, D.,
 1005 Hurley, J., Calcutt, S.B., 2011. Multispectral imaging observations of Neptune's cloud
 1006 structure with Gemini-North. *Icarus* 216, 141–158.
 1007
 1008 Jakubik, M., Morbidelli, A., Neslušan, L., Brasser, R., 2012. The accretion of Uranus
 1009 and Neptune by collisions among planetary embryos in the vicinity of Jupiter and
 1010 Saturn. *Astron. Astrophys.* 540, 16.
 1011

1012 Janhunen, P., et al, 2013. Electric solar wind sail mass budget model. *Geosci. Instrum.*
 1013 *Method. Data Syst.* 2, 85.
 1014
 1015 Karkoschka, E., 2011. Neptune's rotational period suggested by the extraordinary
 1016 stability of two features. *Icarus* 215, 439-448.
 1017
 1018 Karkoschka, E., Tomasko, M.G., 2011. The haze and methane distributions on
 1019 Neptune from HST-STIS spectroscopy. *Icarus* 211, 780–797.
 1020
 1021 Kaspi, Y., Showman, A.P., Hubbard, W.B., Aharonson, O., Helled, R., 2013.
 1022 Atmospheric confinement of jet streams on Uranus and Neptune. *Nature* 497, 344-
 1023 347.
 1024
 1025 Kempf, S., Srama, R., Horányi, M., Burton, M., Helfert, S., Moragas-
 1026 Klostermeyer, G., Roy, M., Grün, E., 2005. High-velocity streams of dust originating
 1027 from Saturn. *Nature* 433, 289-291.
 1028
 1029 Kivelson, M.G., 2004. Moon-magnetosphere interactions: a tutorial. *Adv. Space Res.*
 1030 33, 2061-2077.
 1031
 1032 Krimigis, S.M., Bostrom, C.O., Cheng, A.F., Armstrong, T.P., Axford, W.I., 1989.
 1033 Hot plasma and energetic particles in Neptune's magnetosphere. *Science* 246, 1483-
 1034 1489.
 1035

1036 Krivov, A.V., Wardinski, I., Spahn, F., Krüger, H., Grün, E., 2002. Dust on the
 1037 outskirts of the Jovian system. *Icarus* 157, 436-455.
 1038
 1039 Landau, D.F., et al., 2009. Broad search and optimization of solar electric propulsion
 1040 trajectories to Uranus and Neptune. *Advances in the Astronautical Sciences* 153,
 1041 2093.
 1042
 1043 Laufer, D., Bar-Nun, A., Pat-El, I., Jacovi, R., 2013. Experimental Studies of Ice
 1044 Grain Ejection by Massive Gas Flow from Ice and Implications to Comets, Triton and
 1045 Mars. *Icarus* 222, 73-80.
 1046
 1047 Leinhardt, Z.M., Ogilvie, G.I., Latter, H.N., Kokubo, E., 2012. Tidal disruption of
 1048 satellites and formation of narrow rings. *MNRAS* 424, 1419-1431.
 1049
 1050 Lellouch, E., Hartogh, P., Feuchtgruber, H., Vandenbussche, B., de Graauw, T.,
 1051 Moreno, R., Jarchow, C., Cavalie, T., Orton, G., Banaszkiewicz, M., Blecka, M.I.,
 1052 Bockelee-Morvan, D., Crovisier, J., Encrenaz, T., Fulton, T., Kuppers, M., Lara,
 1053 L.M., Lis, D.C., Medvedev, A.S., Rengel, M., Sagawa, H., Swinyard, B., Szutowicz,
 1054 S., Bensch, F., Bergin, E., Billebaud, F., Biver, N., Blake, G.A., Blommaert, J.A.D.L.,
 1055 Cernicharo, J., Courtin, R., Davis, G.R., Decin, L., Encrenaz, P., Gonzalez, A., Jehin,
 1056 E., Kidger, M., Naylor, D., Portyankina, G., Schieder, R., Sidher, S., Thomas, N., de
 1057 Val-Borro, M., Verdugo, E., Waelkens, C., Walker, H., Aarts, H., Comito, C.,
 1058 Kawamura, J.H., Maestrini A., Peacocke, T., Teipen, R., Tils, T., Wildeman, K.,
 1059 2010a. First results of Herschel-PACS observations of Neptune. *Astron. Astrophys.*
 1060 518, L152.

1061

1062 Lellouch, E., de Bergh, C., Sicardy, B., Ferron, S., Käufl, H.-U., 2010b. Detection of
 1063 CO in Triton's atmosphere and the nature of surface-atmosphere interactions, *Astron.*
 1064 *Astrophys.*, 512, L8, doi: 10.1051/0004-6361/201014339.

1065

1066 Lockwood, G.W., Jerzykiewicz, M., 2006. Photometric variability of Uranus and
 1067 Neptune, 1950-2004. *Icarus* 180, 442–452.

1068

1069 Luszcz-Cook, S.H., de Pater, I., 2013. Constraining the origins of Neptune's CO
 1070 abundance with CARMA millimeter-wave observations. *Icarus* 222, 379-400.

1071

1072 Marley, M. et al., 2010. Planetary Science Decadal Survey JPL Rapid Mission
 1073 Architecture Neptune-Triton KBO Study Final Report.
 1074 <http://solarsystem.nasa.gov/2013decadal/whitepapers.cfm?Category=MS>.

1075

1076 Masters, A., Eastwood, J.P.; Swisdak, M., Thomsen, M.F., Russell, C.T., Sergis, N.,
 1077 Crary, F.J., Dougherty, M.K., Coates, A.J., Krimigis, S.M., 2012. The importance of
 1078 plasma β conditions for magnetic reconnection at Saturn's magnetopause. *Geophys.*
 1079 *Res. Lett.* 39. L08103.

1080

1081 McKinnon, W.B., Lunine, J.I., Banfield, D., 1995. Origin and evolution of Triton. In:
 1082 Cruikshank (Ed.), *Neptune and Triton*, Univ. of Arizona Press, Tucson, pp. 807-877.

1083

1084 McKinnon, W.B., Kirk, R.L., 2007. Triton, in: Lucy-Ann McFadden, L.A.,
 1085 Weissman, P., Johnson, T. (Eds.), *Encyclopedia of the Solar System*. Academic Press,

1086 pp. 483–502.

1087

1088 Morbidelli, A., 2004. How Neptune pushed the outer boundaries of our Solar System.

1089 Science 306, 1302-1304.

1090

1091 Morbidelli, A., Levison, H.F., Tsiganis, K., Gomes, R., 2005. Chaotic capture of

1092 Jupiter’s Trojan asteroids in the early Solar System. Nature 435, 462-465.

1093

1094 Moses, J.I., Fouchet, T., Bezdard, B., Gladstone, G.R., Lellouch, E., Feuchtgruber, H.,

1095 2005. Photochemistry and diffusion in Jupiter’s stratosphere: Constraints from ISO

1096 observations and comparisons with other giant planets. J. Geophys. Res. 110, 8001.

1097

1098 NASA Factsheets, 2013. NF-2013-07-568-HQ,

1099 <http://solarsystem.nasa.gov/rps/home.cfm>.

1100

1101 NASA Radioisotope Power Systems Program Office, 2012. End of Fiscal Year

1102 Report, <http://rps.nasa.gov>.

1103

1104 Ness, N. F., Acuna, M.H., Burlaga, L.F., Connerney, J.E.P., Lepping, R.P., 1989.

1105 Magnetic fields at Neptune. Science 246, 1473-1478.

1106

1107 Nettelmann, N., Helled, R., Fortney, J.J., Redmer, R., 2013. New indication for a

1108 dichotomy in the interior structure of Uranus and Neptune from the application of

1109 modified shape and rotation data. Planet. Space Sci., 77, 143-151.

1110

1111 Neubauer, F. M., 1990. Satellite plasma interactions. *Adv. Space Res.* 10, 25-38.

1112

1113 O'Brien, R.C., Ambrosi, R.M., Bannister, N.P., Howe, S.D., Atkinson, H.V., 2008.

1114 Safe radioisotope thermoelectric generators and heat sources for space applications,

1115 *Journal of Nuclear Materials*, 377 (3), 506-521.

1116

1117 Orton, G.S., Aitken, D.K., Smith, C., Roche, P.F., Caldwell, J., Snyder, R., 1987. The

1118 spectra of Uranus and Neptune at 8-14 and 17-23 microns. *Icarus* 70, 1–12.

1119

1120 Orton, G.S., Encrenaz, T., Leyrat, C., Puetter, R., Friedson, A.J., 2007. Evidence for

1121 methane escape and strong seasonal and dynamical perturbations of Neptune's

1122 atmospheric temperatures. *Astron. Astrophys.* 473, L5–L8.

1123

1124 Orton, G.S., Fletcher, L.N., Liu, J., Schneider, T., Yanamandra-Fisher, P.A., de Pater,

1125 I., Edwards, M., Geballe, T.R., Hammel, H.B., Fujiyoshi, T., Encrenaz, T., Pantin, E.,

1126 Mousis, O., Fuse, T., 2012. Recovery and characterization of Neptune's near-polar

1127 stratospheric hot spot. *Planet. Space Sci.* 61, 161–167.

1128

1129 Pearl, J.C., Conrath, B.J., 1991. The albedo, effective temperature, and energy balance

1130 of Neptune, as determined from Voyager data. *J. Geophys. Res.* 96, 18921-18930.

1131

1132 Postberg, F., Schmidt, J., Hillier, J., Kempf, S., Srama, R., 2011. A salt-water

1133 reservoir as the source of a compositionally stratified plume on Enceladus. *Nature*

1134 474, 620-622.

1135

1136 Prockter, L.M., Nimmo, F., Pappalardo, R.T., 2005. A shear heating origin for ridges
 1137 on Triton. *Geophys. Res. Lett.* 32, L14202, doi: 10.1029/2005GL022832.
 1138
 1139 Quirico, E., Douté, S., Bernard, S., de Bergh, C., Cruikshank, D.P., Owen, T.C., T.R.,
 1140 Roush, T.L., 1999, Composition, Physical State, and Distribution of Ices at the
 1141 Surface of Triton. *Icarus* 139, 159-178.
 1142
 1143 Reynaud, S., Jaekel, M.T., 2005. Testing the Newton law at long distances. *Int. J.*
 1144 *Mod. Phys.* 20, 2294-2303.
 1145
 1146 Richardson, J.D., Belcher, J.W., Zhang, M., McNutt, R.L., 1991. Low-energy ions
 1147 near Neptune. *J. Geophys. Res.* 96, 18993-19011..
 1148
 1149 Ruiz, J., 2003. Heat flow and depth to a possible internal ocean on Triton. *Icarus* 166,
 1150 436-439.
 1151
 1152 Sarsfield, M. J., et al., 2013. Progress on ^{241}Am production for use in Radioisotope
 1153 Power Systems. *Proceedings of Nuclear and Emerging Technologies for Space*,
 1154 Albuquerque, NM, February 25-28.
 1155
 1156 Schenk, P., Jackson, P.A., 1993. Diapirism on Triton: a record of crustal layering and
 1157 instability. *Geology* 21, 299-302.
 1158
 1159 Schenk, P.M., Zahnle, K., 2007. On the negligible surface age of Triton. *Icarus* 192,
 1160 135-147.

1161

1162 Schulz, M., McNab, M.C., Lepping, R.P., Voigt, G.-H., 1995. Magnetospheric
 1163 Configuration of Neptune. In: Cruikshank (Ed.), Neptune and Triton, Univ. of
 1164 Arizona Press, Tucson, pp. 233-277.

1165

1166 Sicardy, B., Roddier, F., Roddier, C., Perozzi, E., Graves, J.E., Guyon, O.,
 1167 Northcott, M.J, 1999. Images of Neptune's ring arcs obtained by a ground-based
 1168 telescope. *Nature* 400, 731-733.

1169

1170 Smith, B.A., Soderblom, L.A., Banfield, D., Barnet, C., Basilevsky, A.T., Beebe,
 1171 R.F., Bollinger, K., Boyce, J.M., Brahic, A., Briggs, G.A., Brown, R.H., Chyba, C.,
 1172 Collins, S.A., Colvin, T., Cook, II, A.F., Crisp, D., Croft, S.K., Cruikshank, D., Cuzzi,
 1173 J.N., Danielson, G.E., Davies, M.E., De Jong, E., Dones, L., Godfrey, D., Goguen, J.,
 1174 Grenier, I., Haemmerle, V.R., Hammel, H., Hansen, C.J., Helfenstein, C.P., Howell,
 1175 C., Hunt, G.E., Ingersoll, A.P., Johnson, T.V., Kargel, J., Kirk, R., Kuehn, D.I.,
 1176 Limaye, S., Masursky, H., McEwen, A., Morrison, D., Owen, T., Owen, W., Pollack,
 1177 J.B., Porco, C.C., Rages, K., Rogers, P., Rudy, D., Sagan, C., Schwartz, J.,
 1178 Shoemaker, E.M., Showalter, M., Sicardy, B., Simonelli, D., Spencer, J., Sromovsky,
 1179 L.A., Stoker, C., Strom, R.G., Suomi, V.E., Synott, S.P., Terrile, R.J., Thomas,
 1180 P., Thompson, W.R., Verbiscer, A., Veverka, J., 1989. Voyager 2 at Neptune -
 1181 Imaging science results. *Science*. 246, 1422-1449.

1182

1183 Soderblom, L. A., Kieffer, S.W., Becker, T. L., Brown, R. H., Cook II, A. F., Hansen,
 1184 C. J., Johnson, T. V., Kirk, R. L., Shoemaker, E. M., 1990. Triton's Geyser-Like
 1185 Plumes: Discovery and Basic Characterization. *Science* 250, 410-415.

1186

1187 Soderlund, K.M., Heimpel, M.H., King, E.M., Aurnou, J.M., 2013. Turbulent models
 1188 of ice giant internal dynamics: Dynamos, heat transfer, and zonal flows. *Icarus* 224,
 1189 97-113.

1190

1191 Spilker, L.J., et al., 2010. Neptune Ring Science with Argo - A Voyage through the
 1192 Outer Solar System. NASA Planetary Decadal Survey 2013-2022.

1193

1194 Srama, R., Kempf, S., Moragas-Klostermeyer, G., Helfert, S., Ahrens, T. J.,
 1195 Altobelli, N., Auer, S., Beckmann, U., Bradley, J.G., Burton, M., Dikarev, V.V.,
 1196 Economou, T., Fechtig, H., Green, S.F., Grande, M., Havnes, O., Hillier, J.K.,
 1197 Horanyi, M., Igenbergs, E., Jessberger, E.K., Johnson, T.V., Krüger, H., Matt, G.,
 1198 McBride, N., Mocker, A., Lamy, P., Linkert, D., Linkert, G., Lura, F.,
 1199 McDonnell, J.A.M., Möhlmann, D., Morfill, G.E., Postberg, F., Roy, M.,
 1200 Schwehm, G.H., Spahn, F., Svestka, J., Tschernjawski, V., Tuzzolino, A.J.,
 1201 Wäsch, R., Grün, E., 2006. In situ dust measurements in the inner Saturnian system.
 1202 *Planet. Space Sci.*, 54, 967-987.

1203

1204 Sromovsky, L.A., Fry, P.M., Dowling, T.E., Baines, K.H., Limaye, S.S., 2001.
 1205 Coordinated 1996 HST and IRTF Imaging of Neptune and Triton. III. Neptune's
 1206 Atmospheric Circulation and Cloud Structure. *Icarus* 149, 459–488.

1207

1208 Stanley, S., Bloxham, J., 2004. Convective-region geometry as the cause of Uranus'
 1209 and Neptune's unusual magnetic fields. *Nature* 428, 151,153.

1210

1211 Stern, S.A., McKinnon, W.B., 2000. Triton's surface age and impactor population
 1212 revisited in light of Kuiper belt fluxes: evidence for small Kuiper belt objects and
 1213 recent geological activity. *Astron. J.* 119, 945-952.
 1214
 1215 Stone, E.C., Miner, E.D., 1989. The Voyager 2 encounter with the Neptunian system.
 1216 *Science* 246, 1417-1421.
 1217
 1218 Stone, E.C., Cummings, A.C., Looper, M.D., Selesnick, R.S., Lal, N.,
 1219 McDonald, F.B., Trainor, J.H., 1989. Energetic charged particles in the
 1220 magnetosphere of Neptune. *Science* 246, 1489-1494.
 1221
 1222 Strobel, D.F., Cheng, A.F., Summers, M.E., Strickland, D.J., 1990. Magnetospheric
 1223 interaction with Triton's ionosphere. *Geophys. Res. Lett.* 17, 1661-1664.
 1224
 1225 Tiscareno, M. S., Hedman, M.M., Burns, J.A., Castillo-Rogez, J., 2013. Compositions
 1226 and origins of outer planet systems: insights from the Roche critical density. *Ap. J.*
 1227 *Lett.* 765, 5.
 1228
 1229 Tsiganis, K., Gomes, R., Morbidelli, A., Levison, H.F., 2005. Origin of the orbital
 1230 architecture of the giant planets of the Solar System. *Nature* 435, 459-461.
 1231
 1232 Tyler, G. L., Sweetnam, D.N., Anderson, J.D., Borutzki, S.E., Campbell, J.K.,
 1233 Kursinski, E.R., Levy, G.S., Lindal, G.F., Lyons, J.R., Wood, G.E., 1989. Voyager
 1234 Radio Science Observations of Neptune and Triton. *Science* 246, 1466-1473.
 1235

- 1236 Will, C.M., 2006. The confrontation between general relativity and experiment.
1237 Living Rev. Relativity 9, 1.
1238
1239 Zarka, P., Pedersen, B.M., Lecacheux, A., 1995, Radio emission from Neptune. In:
1240 Cruikshank (Ed.), Neptune and Triton, Univ. of Arizona Press, Tucson, pp. 341-387.
1241
1242

1243 Figure captions

1244

1245 Figure 1. Neptune, captured by the *Voyager 2* narrow-angle camera. Credit:

1246 NASA/JPL.

1247

1248 Figure 2. The orbital evolution of the outer Solar System. The three panels show

1249 sketches of the beginning, middle, and end of planetary migration. The disk

1250 planetesimals are coloured, depending on whether they have had close encounters

1251 with Neptune (grey) or not (red). From Morbidelli (2004).

1252

1253 Figure 3. Chart showing Neptune's poorly understood interior based on current

1254 observational constraints.

1255

1256 Figure 3. Neptune's poorly understood interior. (a, b) Illustrations of the importance

1257 of atmospheric abundance measurements (here: D/H and CO) for constraining the ice

1258 mass fraction in the outer envelope (Z₁), and thus the interior structure. (c) Pie chart

1259 illustrating current understanding of the Neptunian interior.

1260

1261 Figure 4. Hubble Space Telescope images of Neptune's rapidly evolving cloud

1262 systems, taken just a few hours apart (left). High-altitude clouds seen by *Voyager 2*

1263 (right), credit: NASA/JPL.

1264

1265 Figure 5. Image of the Adams and Leverrier ring (outer and inner curve, respectively)

1266 taken by the *Voyager 2* wide-angle camera. The brightest parts of the Adams ring are

1267 the ring arcs. Credit: NASA/JPL.

1268

1269 Figure 6. The changing configuration of Neptune's magnetosphere under solstice
1270 (southern summer) conditions. The noon-midnight plane is shown, with the planetary
1271 dipole (red arrow) captured at positions separated by half a planetary rotation period.
1272 Credit: Steve Bartlett & Fran Bagenal.

1273

1274 Figure 7. Triton and a binary companion as they approached Neptune. Such an
1275 encounter may have facilitated Triton's capture by Neptune, an event that
1276 catastrophically altered the Neptune satellite system. In the image Neptune is orbited
1277 by several primordial satellites that may have existed prior to the encounter, but were
1278 destroyed in its aftermath.

1279

1280 Figure 8. Global mosaic of Triton's surface. The southern polar cap covers the lower
1281 part of the imaged region of the surface. At lower latitudes the cantaloupe terrain and
1282 plains are in the West and the East, respectively. Credit: NASA/JPL/USGS.

1283

1284 Figure 9. Profile of Triton's atmosphere based on radio data and models. From Tyler
1285 et al. (1989).

1286

1287 Figure 10. Triton's magnetospheric interaction, showing the expected Alfvén wings.
1288 From Strobel et al. (1990).

1289

1290 Figure 11. Neptune orbiter mission analysis. (a) Example interplanetary transfer with
1291 launch in 2028. Trajectory arcs where solar electric propulsion is employed are

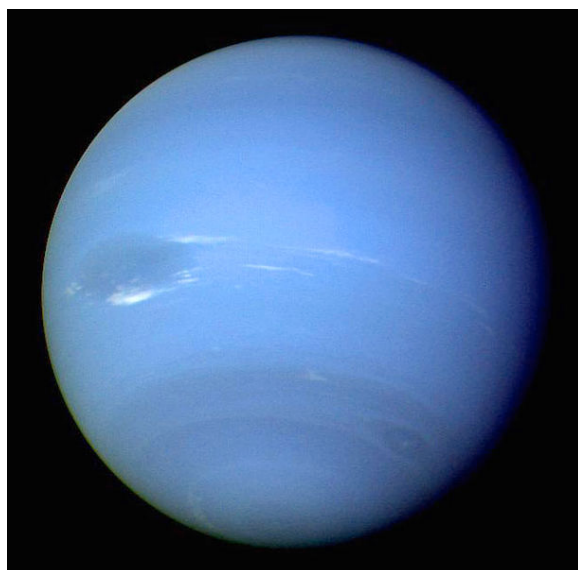
1292 represented by red arrows. (b) Example Neptune orbital tour, viewed from Neptune's
1293 north pole.

1294

1295

1296 Figures

1297



1298

1299

1300 Figure 1.

1301

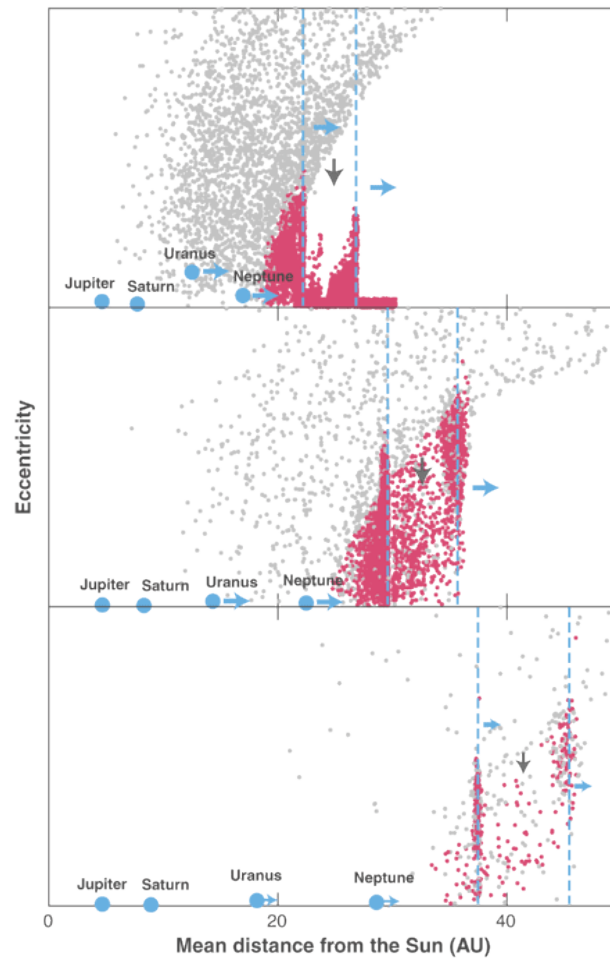


Figure 2.

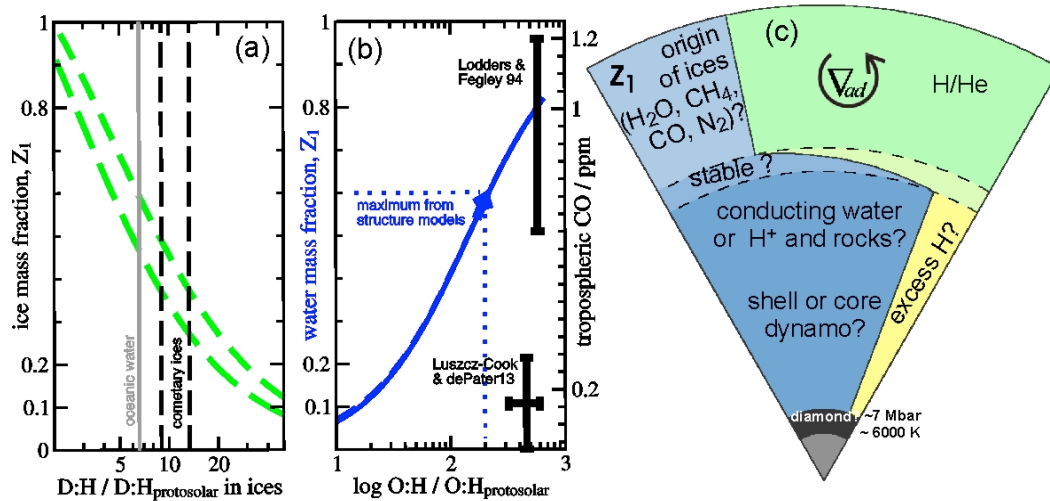
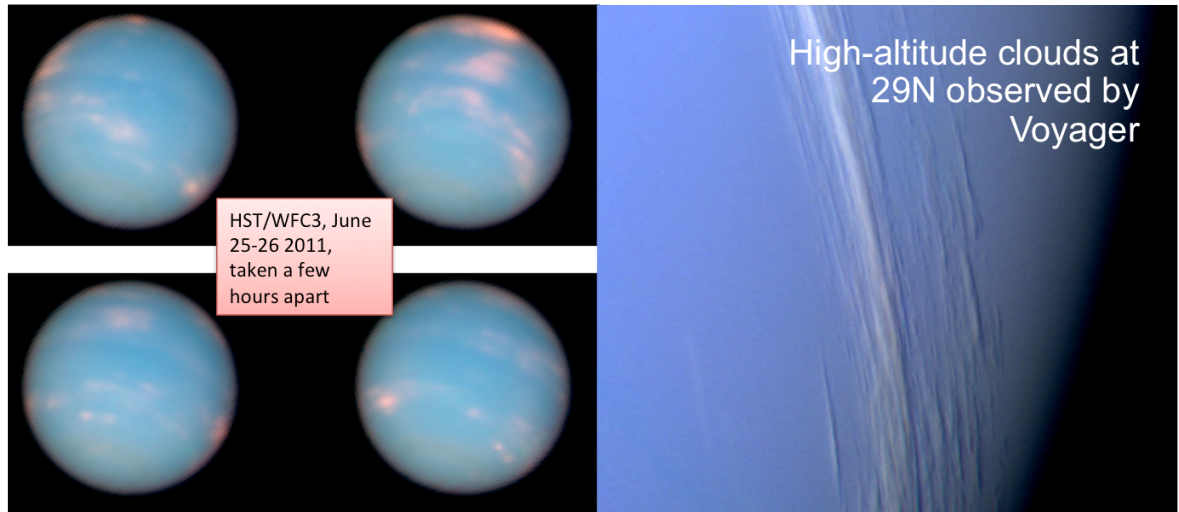


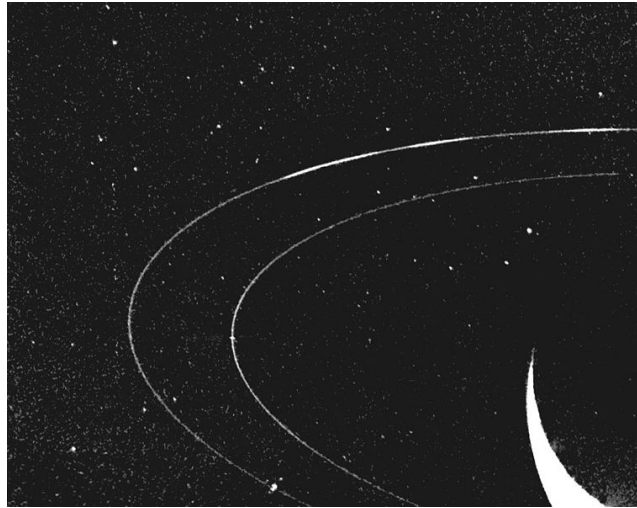
Figure 3.



1310

1311 Figure 4.

1312



1313

1314

1315 Figure 5.

1316

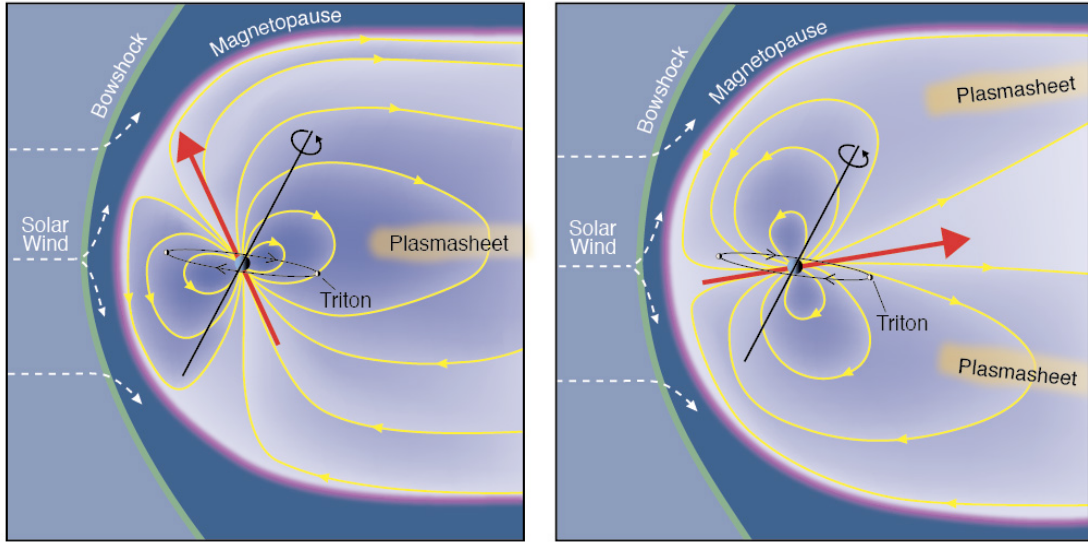
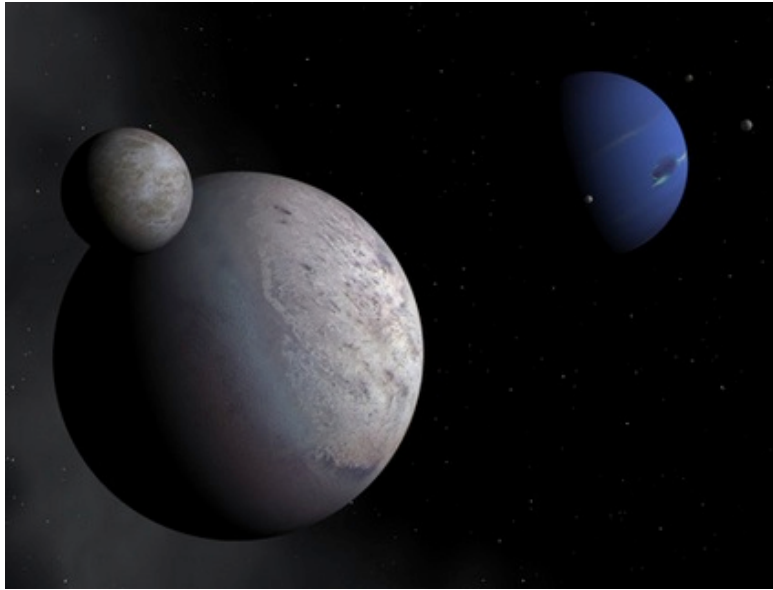


Figure 6.

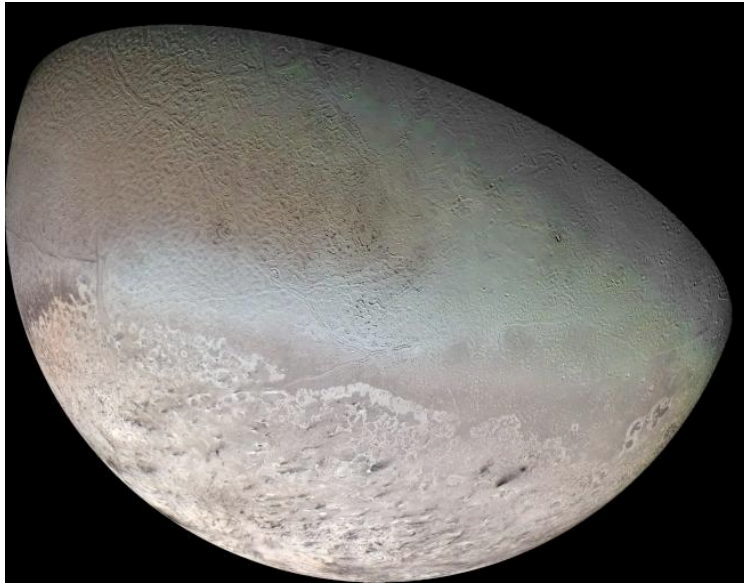


1320

1321

1322 Figure 7.

1323



1324

1325

1326 Figure 8.

1327

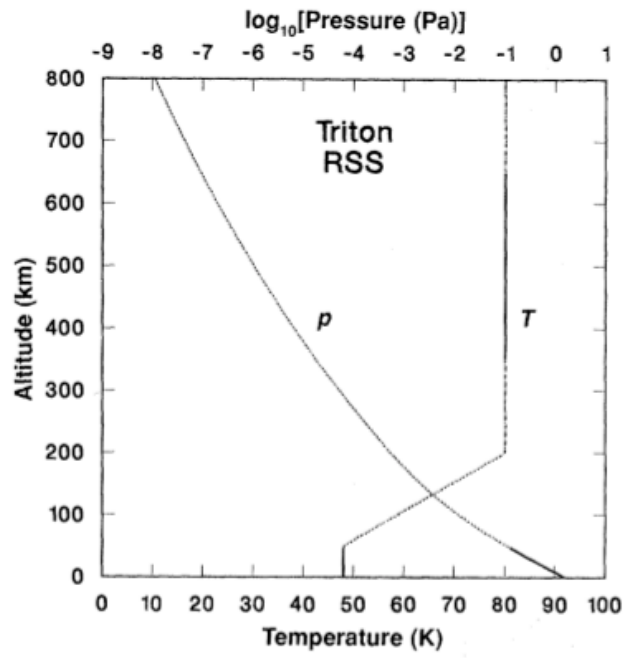
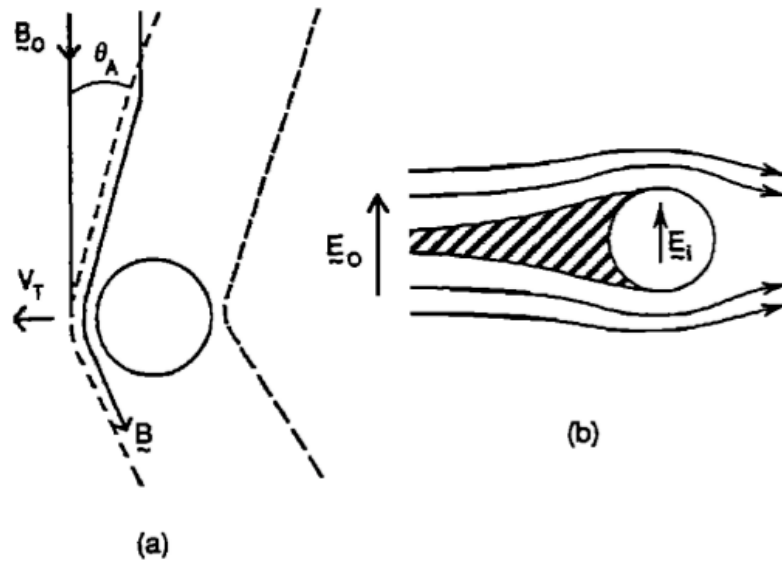


Figure 9.



1331

1332 Figure 10.

1333

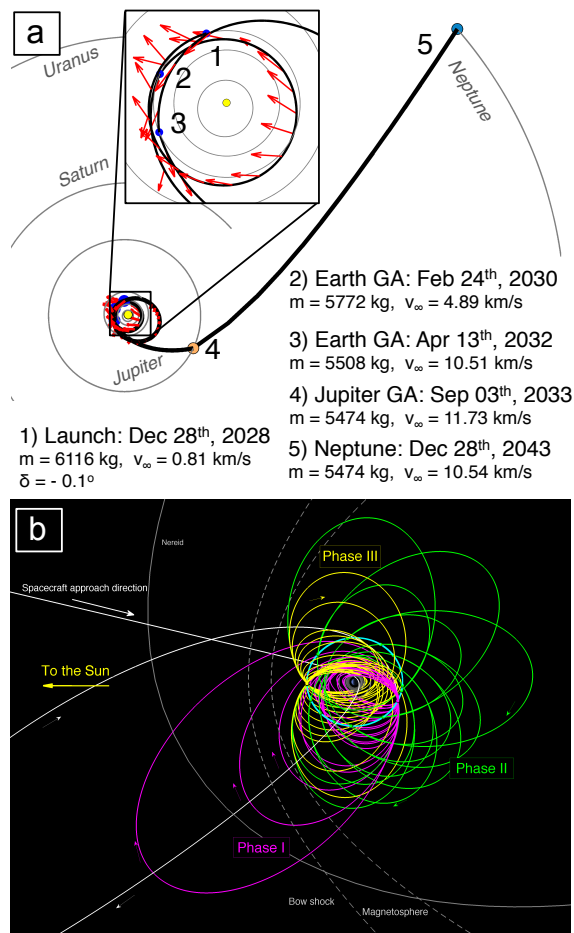


Figure 11.

1338

Interplanetary mission profile	Launch on 28 Dec 2028 with Ariane 5 ECA. Two Earth Gravity Assists (GA) + 1 Jupiter GA. Transfer time: 15 years. Propulsion: Solar Electric Propulsion (SEP, ejected before Jupiter flyby), total propellant mass of 642 kg.
Neptune tour mission profile	Two-year orbital tour (covering all solar local times and a range of orbital inclinations). 55 Triton flybys (providing global surface coverage). Propulsion: Chemical, total Delta-V of 3 km s ⁻¹ .
Power sub-system	10 European radioisotope thermoelectric generators, providing 500 W at Neptune
Mass budget	Mass at launch: 6116 kg SEP module wet mass: 1500 kg Dry mass at Neptune: 1800 kg Payload mass: 70 kg

1339

1340 Table 1. Overview of a recent analysis of an ESA-led Neptune orbiter mission.