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## 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.

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

2

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53

54 Abstract

55

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

75

76 Keywords: Neptune, Triton

77

78 1. Introduction

79

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

86 Neptune is classified as one of the gas giant planets, along with Jupiter,  
87 Saturn, and Uranus, and additionally forms a subgroup with Uranus called the “ice  
88 giants”, because both planets are primarily composed of “ices” (volatile elements  
89 heavier than hydrogen and helium). However, there are fundamental and important  
90 differences between the Uranus and Neptune planetary systems, which their common  
91 classification as ice giant planets should not obscure. The Neptune system is unique,  
92 providing opportunities for major advances across multiple scientific fields that  
93 cannot be made in any other planetary environment.

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

101 *Voyager 2* is the only spacecraft that has encountered Neptune to date, flying  
102 by the planet on 25 August 1989 when it was summer in Neptune’s southern

103 hemisphere (Stone and Miner, 1989). Figure 1 shows *Voyager 2* imaging of Neptune  
104 during approach to the planet (Smith et al., 1989). The combination of this brief  
105 encounter and ground-based and space-based telescope observing campaigns have  
106 shown us that Neptune has the most meteorologically active atmosphere in the Solar  
107 System, despite its distance from the Sun, and that Triton has been (and could  
108 currently be) geologically active (see the review by Cruikshank (1995)). The Neptune  
109 system is barely explored compared to other planetary systems, and never with  
110 modern spacecraft instrumentation.

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

120

## 121 2. Neptune

122

### 123 2.1. Formation and Implications for the Solar System and Exoplanets

124

125 While there has been debate about Neptune's formation, a leading theory has now  
126 emerged (Gomes et al., 2005; Tsiganis et al., 2005; Morbidelli et al., 2005). It is  
127 postulated that Neptune formed at around 12-15 AU via planetesimal accumulation,

128 before migrating to its present orbit at  $\sim 30$  AU through a process of angular  
129 momentum exchange with a disk of planetesimals that initially extended out to 30-35  
130 AU, interacting with the planets via gravitational scattering (Tsiganis et al., 2005).  
131 This scenario is supported by the higher density of solid material closer to the Sun  
132 (typical of protoplanetary disks) that would have lead to a shorter planetary accretion  
133 time, and explains the dynamical structure of the Kuiper Belt ( $\sim 30$ -50 AU, remnants  
134 of the planetesimal disk), the possible occurrence of the cataclysmic late heavy  
135 bombardment on the terrestrial planets, and the observed compositional diversity of  
136 the asteroid belt.

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

150         One of the mysteries concerning Neptune's formation stems from the fact that  
151 it had to form after Jupiter and Saturn, since it did not accrete as much gas as these  
152 two other giant planets. Its core likely reached completion in the later stages of solar



153 nebula evolution, when the gas density was low due to viscous accretion and  
154 photoevaporation. How the growth and migration of Jupiter and Saturn delayed the  
155 accretion of Neptune’s atmosphere is not completely clear (Jakubik et al., 2012). In  
156 this context, a detailed knowledge of the chemistry and composition of Neptune’s  
157 atmosphere is essential for understanding how, where, and when the planet accreted  
158 it.

159         Focus on Neptune has intensified recently due to the discovery of numerous  
160 exoplanets with similar physical characteristics, like Gliese 436 b or GJ 3470 b. In  
161 fact, Neptune-sized and sub-Neptune-sized planets are harboured by 3-31% of the  
162 Sun-like stars (Fressin et al., 2013). While Uranus appears to have been radically  
163 altered by collisional processes, producing low internal heat flux, Neptune appears to  
164 have only been subject to scattering processes and is therefore expected to be more  
165 typical of these exoplanets of similar size, possibly sharing a similar evolution. A  
166 better knowledge of Neptune’s physical properties will shed new light on the  
167 formation and characteristics of these exoplanets.

168

169 Key scientific questions:

- 170 • How and where did Neptune form?
- 171 • What role did Neptune play in early Solar System dynamics?
- 172 • What does Neptune tell us about the numerous exoplanets of similar mass?
- 173 • Are Neptune-sized exoplanets “ice giants”?

174

175 2.2. Interior

176

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

188         The *Voyager 2* encounter with Neptune provided us with some constraints on  
189 Neptune's interior. Prior to the encounter, Neptune was thought to be layered in the  
190 form of a rocky core, surrounded by an ice shell and a hydrogen/helium envelope.  
191 *Voyager* data indicated a light-element component in Neptune's deep interior, and a  
192 transition from a hydrogen/helium-rich to an icy/rock-rich interior at about 60-80% of  
193 the planetary radius (Hubbard et al., 1995). Our current, still very limited,  
194 understanding of Neptune's interior is illustrated in Figure 3.

195         Models constrain the light-element mass fraction in Neptune's deep interior to  
196 be 0-30% (Nettelmann et al., 2013), but this range allows for a variety of  
197 fundamentally different scenarios. For instance, a low light-element mass fraction  
198 could be explained by excess hydrogen originating from an initial water, ammonia  
199 and methane-rich composition, which was dissociated under high pressures and  
200 underwent phase separation into a hydrogen-oxygen phase and a carbon-nitrogen  
201 phase. The latter phase may have produced a diamond core. In contrast, a high light-

202 element abundance would indicate simultaneous accretion of small planetesimals and  
203 gas, as well as a rock-rich deep interior.

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

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

221

222 Key scientific questions:

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

227

### 228 2.3. Atmosphere

229

230 Despite its distance from the Sun, Neptune displays some of the most dramatic  
231 meteorological and chemical activity of any atmosphere in our Solar System,  
232 displaying zonal banding, dark ovals and sporadic clouds, along with the fastest wind  
233 speeds measured in any planetary atmosphere (up to 450 m/s, compared with 30-100  
234 m/s on Earth (Hammel et al., 1989; Ingersoll et al., 1990; Sromovsky et al., 2001)).  
235 Discrete cloud features, potentially comprising ices of methane and ammonia, have  
236 been observed in the visible and near-infrared, ranging from the main cloud deck at 2-  
237 3 bars up to altitudes above the tropopause at 100 mbar (e.g. Smith et al., 1989;  
238 Karkoschka, 2011; Irwin et al., 2011). Powerful zonal winds and strong latitudinal  
239 variations lead to significant shears, tearing clouds apart on timescales of hours, as  
240 shown in Figure 4.

241         Given that the solar input at Neptune is only a fraction of that received by  
242 Jupiter, this strong atmospheric activity may be driven by a huge reservoir of internal  
243 heat left over from the planet's formation (see Section 2.2). Indeed, Neptune's  
244 internal heat flux produces emissions that exceed solar input by a factor of 2.6, the  
245 largest of any planet in the Solar System (Pearl and Conrath, 1991), and in stark  
246 contrast with Uranus' apparently negligible internal heat flux.

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

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

267         Some of the basic dynamical, chemical, and cloud-forming processes at work  
268 within Neptune's churning atmosphere are unknown. Neptune's atmospheric  
269 composition is determined by condensation chemistry, vertical mixing, external influx  
270 of oxygenated species from infalling comets and dust (e.g. Lellouch et al., 2010a), and  
271 a rich hydrocarbon photochemistry due to the UV destruction of methane (e.g. Orton  
272 et al., 1987; Moses et al., 2005; Greathouse et al., 2011). Knowledge of elemental  
273 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  
274 abundances (especially the He/H<sub>2</sub> ratio) would provide constraints on the delivery of  
275 these materials to the forming proto-Neptune, and early Solar System conditions.  
276 Furthermore, mapping the spatial distributions of cloud-forming volatiles,

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

286

287 Key scientific questions:

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

294

295 2.4. Rings and small icy satellites

296

297 Although all giant planets shelter a ring system, Neptune's ring system is unique  
298 because it consists of a collection of concentric and semi-transparent ringlets  
299 embedded in a tenuous sheet of dust. The Neptunian rings are tightly gravitationally  
300 coupled to a rich system of moonlets. Between the ringlets orbit a number of small  
301 moons (Naïad, Thalassa, Despina, Galatea). Both the rings and moons are especially

302 dark, and the coupling between them is likely to be of key importance. The rings  
303 contain up to 70% dust in some regions (Smith et al., 1989), which makes them  
304 fundamentally different from Saturn's rings, which contain less than 1% dust. The  
305 origin of this difference in composition is still a mystery, and could be the signature of  
306 different formation/evolutionary processes.

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

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

325 Neptune has 6 regular moons orbiting within 5 planetary radii, forming a  
326 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  $\sim 0.5$   
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

377 the solar wind flow that envelopes most of the Neptunian satellites, including Triton.  
378 Neptune's large dipole tilt angle leads to dramatic changes in the magnetosphere in  
379 only half a planetary rotation period (~8 hrs), passing successively from an Earth-like  
380 to a pole-on configuration (magnetic axis parallel to the solar wind flow) every half a  
381 rotation, as illustrated in Figure 6.

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

391         The relative importance of sources and sinks of plasma in Neptune's  
392 magnetosphere is also unknown (Belcher et al., 1989; Gurnett et al., 1989; Krimigis et  
393 al., 1989; Stone et al., 1989). Triton is thought to be an important source (Richardson  
394 et al., 1991) (see Section 3), as well as charged dust particles harboured by the  
395 planet's rings. Triton makes the Neptunian magnetosphere a vital link between  
396 magnetospheres with similar internal sources of plasma but simpler internal fields  
397 (Jupiter and Saturn), and those with similar magnetic complexity but lacking such  
398 sources (Uranus). In particular, the presence/absence of a Triton plasma torus may  
399 explain the mysterious lack of a clear torus in Saturn's magnetosphere due to the  
400 moon Titan. Strong dust-plasma interactions may produce charged dust streams like  
401 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, H<sub>2</sub> 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  $\beta$  (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

427

428 3.1. Origin and implications for the Neptune system

429

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

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

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

449 Driven to crossing orbits by Triton's perturbations, Neptune's inner satellites  
450 would collide at such large velocities that they would suffer catastrophic disruption  
451 and grind each other down into a debris disk (Goldreich et al., 1989). In this view,

452 Neptune's inner satellites are either the shards left over from this process or second-  
453 generation satellites that accreted from the rings and debris disk (Crida and Charnoz,  
454 2012) (see Section 2.4). In either case, the inner satellite system has experienced  
455 extreme collisional processing. Neptune's distant irregular satellites exterior to  
456 Triton were gravitationally sculpted by Triton following its capture with satellite  
457 material being exchanged between the inner and outer regions through a variety of  
458 dynamical mechanisms.

459 Triton itself may have accumulated a significant portion of its mass ( $\sim > 20\%$ )  
460 from the debris disk (Cuk and Gladman, 2005). The accretion of this material would  
461 have hastened Triton's orbital decay, and rendered it a composite of heliocentric and  
462 planetocentric material. Triton's orbital decay was ultimately dominated by tidal  
463 friction, and the heating during this epoch is expected to be sufficient for global  
464 melting of Triton, and the formation of subsurface oceans (McKinnon et al., 1995).

465

466 Key scientific questions:

- 467 • What physical memory does Triton retain of its heliocentric origins as an icy dwarf  
468 planet?
- 469 • How did Triton evolve after it was captured, and how did Triton affect the Neptune  
470 planetary system?
- 471 • What are the similarities and differences between Triton and the dwarf planets of  
472 the Kuiper Belt?

473

474 3.2. Interior and surface

475

476 The current state of our knowledge of Triton is based on very few observations  
477 (*Voyager 2*) and models. As a result, everything we think we know is subject to  
478 significant uncertainty, and there are fundamental questions that we have no answer to  
479 at present. What little we know includes a relatively high mean density ( $2.065 \text{ g cm}^{-3}$ ),  
480 implying that Triton is composed of a high proportion of rock and metal (~65-70%)  
481 compared to ice. Triton's orbital history and surface geology suggest an important  
482 role for tidal heating in the past (e.g. McKinnon et al., 1995) (see Section 3.1), which  
483 may have produced a differentiated interior with separation of ices, rocks, and metals.  
484 Triton could have a metallic core, silicate mantle, and internal liquid ocean between  
485 ice layers (Hussmann et al., 2006; McKinnon and Kirk, 2007).

486 Triton's surface is composed of ices, mostly  $\text{N}_2$  (which includes  $\text{CO}$ ,  $\text{CH}_4$ , and  
487  $\text{C}_2\text{H}_6$  in solution), with seasonal polar deposits, plus  $\text{H}_2\text{O}$ , and  $\text{CO}_2$  (Quirico et al.,  
488 1999). Triton's surface has a young appearance, indicated by the sparseness and  
489 limited size of unambiguous impact craters, Crater counts indicate a surface age of  
490 several tens to hundreds of millions of years, but that in places the surface age could  
491 be as young as a few million years (Stern and McKinnon, 2000; Schenk and Zahnle,  
492 2007). Triton's surface is therefore one of the younger surfaces in the Solar System,  
493 strongly suggesting that Triton is currently a geologically active satellite.

494 Triton's surface shows a variety of terrains very different to those in other icy  
495 satellites. There are two major types of geological terrains (Smith et al., 1989; Croft et  
496 al., 1995), and a large polar cap of solid nitrogen ice covers a significant fraction of  
497 the southern hemisphere. Figure 8 shows *Voyager 2* imaging of the different terrain  
498 types. A substantial portion of the surface away from the polar cap that could be  
499 imaged by *Voyager 2* during its flyby appears to be occupied by expanses of regularly  
500 spaced, nearly circular depressions, dubbed cantaloupe terrains. The depressions are a

501 few tens of kilometres wide and have a complex morphology. This kind of terrain has  
502 been interpreted to have been formed through compositional diapirism affecting a ~20  
503 km thick crustal layer (Schenk and Jackson, 1993). The other terrain type consists of  
504 undulating or smooth plains that show a variety of landforms, including terraces, and  
505 depressions filled with smooth materials and “ice lakes”. The transition between both  
506 terrain types is characterized by the progressive flooding and disappearance of the  
507 cantaloupe texture, suggestive of onlapping by smooth materials emplacement.

508         The surface is also deformed by a global network of ridges and troughs, more  
509 visible on the cantaloupe terrains and partly flooded at some locations on the plains  
510 (Croft et al., 1995). The ridges morphologically resemble those seen at Jupiter’s moon  
511 Europa (Prockter et al., 2005), although they are much less numerous.

512         The brittle lithosphere (the outermost rigid layer of Triton) is estimated to be  
513 ~10-15 km thick (Ruiz, 2003), which implies heat flows at the time when the surface  
514 was deformed that were clearly higher than those associated with the total radioactive  
515 heat production in the rocky portion of the satellite. Thus, observed resurfacing,  
516 geological activity, and the relatively thin lithosphere could have been caused by the  
517 heat generated during the capture of Triton, or by later release of the remaining heat.  
518 Indeed, tidal heating should be comparatively reduced in the current orbital  
519 eccentricity (Gaeman et al., 2013).

520         *Voyager 2* observed at least two plumes of nitrogen gas and dust at Triton’s  
521 southern polar cap, which erupted from beneath the surface, extended up to 8 km  
522 above it, and were then dragged by atmospheric winds (Soderblom et al., 1990) (see  
523 Section 3.3). These plumes are interpreted to be consequence of geyser-like activity,  
524 which could be powered by insulation-driven heating of the nitrogen cap (Soderblom  
525 et al., 1990). However, an endogen origin (driven by internal heat) cannot be currently

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

529

530 Key scientific questions:

- 531 • What is the composition, structure, and heat flow from Triton's interior?
- 532 • What is the age of features on Triton's surface?
- 533 • How geologically active is Triton and what drives the plumes?

534

### 535 3.3. Atmosphere

536

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

543 Triton's atmosphere appears to be nitrogen-rich, and sustained by ices at the  
544 surface in vapour pressure equilibrium with the atmosphere. It has been likened to the  
545 atmosphere of Pluto. Currently known additional species in Triton's atmosphere are  
546 trace amounts of volatile gases, including methane and carbon monoxide. Trace  
547 amounts of CH<sub>4</sub>, less than those in the atmospheres of Saturn's moon Titan or Pluto,  
548 were discovered using ultraviolet observations made by *Voyager* (Broadfoot et al.,  
549 1989). CO was first observed using the European Southern Observatory Very Large  
550 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 ( $14\text{-}19$   $\mu\text{bar}$ ) (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  $\sim 38$  K. Triton's atmosphere is seasonally  
555 variable, as the  $\text{CH}_4$  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  $\sim 1$   $\mu\text{m}$  in size (Smith et al., 1989). Triton lacks a stratosphere, but has a  
561 thermosphere between  $\sim 8$  and  $\sim 950$  km, and an exosphere above. The temperature of  
562 the upper atmosphere is  $\sim 95$  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?

576

577 3.4. Interaction with Neptune's magnetosphere

578

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

587 Triton has an ionosphere at the top of its tenuous atmosphere with a peak  
588 density at ~340km, as determined by radio science observations. One surprise  
589 revealed by these data was the observed high ionospheric density of ~46,000 cm<sup>-3</sup>  
590 (Tyler et al., 1989); this is higher than that in the ionosphere of Saturn's moon Titan,  
591 which also has a nitrogen-based atmosphere. This is surprising because the solar  
592 illumination is a factor of ~10 lower at Triton than at Titan. The high density has been  
593 suggested to be due to the impact of energetic (>10 keV) precipitating particles from  
594 Neptune's magnetosphere (Strobel et al., 1990). The measured energy flux of >22keV  
595 particles well away from Triton is ~2 orders of magnitude greater than sunlight  
596 (Krimigis et al., 1989), but this will reduce significantly when Triton is far from the  
597 planetary magnetic equator.

598 Due to the geometry and closest approach distance of the *Voyager 2* encounter  
599 with Triton, the moon-magnetosphere interaction has never been measured directly.  
600 Triton regularly visits different regions of Neptune's magnetosphere (magnetic

601 L-shells between 14.3 and  $\gg 40 R_N$  (Ness et al., 1989)) and is subject to different  
602 particle fluxes, and thus different coupling between the magnetosphere, atmosphere,  
603 and possibly Triton's surface. There is also a complex seasonal cycle, which must  
604 provide interesting and possibly significant effects.

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

612

613 Key scientific objectives:

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

621

622 3.5. Habitability

623

624 Since the era of the *Voyager* planetary encounters subsurface oceans have been  
625 identified at three of Jupiter's moons (Europa, Ganymede, and Callisto), and there is

626 indirect evidence for two of Saturn's moons (Enceladus and Titan) (e.g. Kivelson,  
627 2004). Subsurface oceans may be a common feature of icy moons in the Solar  
628 System, and a subsurface water ocean is predicted at Triton (McKinnon et al., 1995;  
629 Hussmann et al., 2006; McKinnon and Kirk, 2007). Water is thought to be a key  
630 requirement for the habitability of such an ocean. *Cassini* observations at Saturn's  
631 moon Enceladus have demonstrated that dust in the surrounding environment can  
632 potentially reveal the composition of any subsurface ocean (Postberg et al., 2011).

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

644

645 Key scientific questions:

- 646 • Does Triton have a subsurface ocean, and, if so, what are its properties and  
647 composition?
- 648 • Is the chemical environment favourable for habitability?
- 649 • How does Triton compare to other Solar System moons of astrobiological interest?

650

651 4. Science during an interplanetary cruise to Neptune

652

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

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

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

672 Given the expected higher volatile content of these outer Solar System small  
673 bodies compared to the typical makeup of such objects residing closer to the Sun,  
674 scientific observations in the vicinity of such bodies beyond the orbit of Jupiter would  
675 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

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

702 *Fundamental Physics: Testing General relativity.* Interplanetary space  
703 approaching Neptune is of great importance as an environment in which we can test  
704 the limits of contemporary physics. General Relativity (GR), the current theoretical  
705 formulation of gravitation, is in good agreement with most experimental tests (Will,  
706 2006). However, GR is a classical theory, and all attempts to merge it with the  
707 quantum description of the other fundamental interactions suggest it cannot be the  
708 final theory of gravitation. Meanwhile, experimental tests leave open windows for  
709 deviations from GR at small (Adelberger et al., 2009) and large distances (Reynaud  
710 and Jaekel, 2005).

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

721 A crucial question when addressing the nature of dark matter and dark energy  
722 is whether or not GR is the correct description of gravity at large scales, like distances  
723 approaching that between the Sun and Neptune. Addressing this question is essential  
724 in order to bridge the gap between experiments in the Solar System and astrophysical

725 or cosmological observations. Probing the limits of current gravitation theory is also  
726 closely related to the problem of Solar System formation and evolution, including the  
727 formation of the Neptune planetary system (see Section 2.1).

728

729 Key scientific questions:

- 730 • What are the characteristics of the Centaurs in the outer Solar System?
- 731 • How many of these Centaurs are active?
- 732 • How do dust properties vary from Earth to Neptune?
- 733 • Do solar wind properties in the outer Solar System agree with model predictions?
- 734 • How do solar wind transients evolve from the Sun to ~30 AU, and what does this  
735 mean for Neptune's magnetospheric dynamics?
- 736 • Is general relativity the correct description of gravity at scales approaching the  
737 Sun-Neptune distance?
- 738 • If not, how does this change our understanding of Solar System formation and  
739 evolution, and the dark matter/dark energy problem?

740

741 5. Neptune orbiter mission analysis

742

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



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

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

759

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

770

771 2. Radioisotope Thermoelectric Generators (RTGs) or Stirling Radioisotope  
772 Generators (SRGs). The issue of electrical power for any mission beyond Jupiter  
773 makes RTGs or SRGs an enabling technology for a Neptune orbiter. European RTG

774 development activities are currently targeting a maximum electrical power output of  
775 50 W, with SRGs targeting 100 W. The European program to develop RTGs is  
776 currently at TRL ~3 (Ambrosi et al., 2012). The radioisotope chosen for the European  
777 space nuclear power program is Americium-241 (Sarsfield et al., 2013, O'Brien et al.  
778 2008) which has a longer half-life (433 years) when compared to Plutonium-238 (88  
779 years); however, Plutonium-238 has been used in RTG systems for more than half a  
780 century. The current European RTG lifetime requirement is 20 years. Given that  
781 americium has a half-life, which is much longer than any nominal mission lifetime,  
782 isotope decay will not be a limiting factor. Considering that historically spacecraft  
783 powered by RTG systems have exceeded their nominal mission lifetimes, for  
784 example, Pioneer 10 exceeded its nominal 2 year mission by several decades (Dyal  
785 1990) and Voyager 1 is still transmitting data. Extended lifetime testing of European  
786 RTG and SRG solutions will reduce any uncertainties in lifetime values; however,  
787 this type of activity will be part of future studies. US ASRG designed for at least 17-  
788 year mission life (NASA, 2013) are currently undergoing extended lifetime testing  
789 (NASA, 2012). If we take the nominal power requirement of a Neptune orbiter  
790 mission to be 500 W, 10 European RTGs or 5 SRGs would be sufficient, producing a  
791 total electric power of 500 W. In the case of RTGs the mass would be of order 250 kg,  
792 assuming a nominal specific power of 2.0 W/kg, which is the current target of a study  
793 led by a UK team (Ambrosi et al., 2012). Assuming a 20% maturity margin, the total  
794 mass would be ~300 kg. Specific power values for European SRG solutions will be  
795 determined as at the end of a current ESA study. SRG solutions for a mission to the  
796 outer planets after 2028 should not be excluded at this stage and should form part of  
797 future more detailed mission trade-off studies.

798

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.

823 Interplanetary transfer to Neptune requires a Gravity Assist (GA) by either  
824 Jupiter or Saturn a few years after launch because of RTG lifetime and to mitigate  
825 propellant requirements. However, a Jupiter GA is more effective than a Saturn GA  
826 for a Neptune orbiter mission (Landau et al., 2009). Favourable opportunities for a  
827 Jupiter GA will exist in 2033 and in 2046 (separated by a Jupiter-Neptune synodic  
828 period of  $\sim 13$  years). This example takes advantage of the 2033 Jupiter GA  
829 opportunity. A mission-enabling SEP module is employed early in the transfer (see  
830 Figure 11), but the module is ejected prior to the Jupiter GA.

831 Regarding the Neptune orbital tour, we would like to highlight that Triton is  
832 an effective “tour engine”, allowing a wide range of orbit trajectories and observation  
833 opportunities. Our example tour is 2 years in duration, starting with interplanetary  
834 transfer arrival conditions given by the first stage of this mission analysis. At the  
835 beginning of the tour the spacecraft flies between the inner rings and executes NOI at  
836 3,000 km altitude, following previous NASA mission concepts (Marley et al., 2010).  
837 During the three phases of this example tour there are inclined Neptune orbits, orbits  
838 in Triton’s orbital plane, and 55 Triton flybys that cover the full range of Triton  
839 orbital locations, and altitudes between  $\sim 150$  and  $\sim 1,000$  km. There is significant  
840 flexibility in, for example, Triton flyby altitudes, which can be raised or lowered as  
841 necessary. Our preliminary analysis suggests that a Triton orbit phase could be  
842 included at a Delta-V cost of  $\sim 300$  m/s, using a transfer similar to that planned for  
843 *JUICE* (Campagnola et al., 2012). Close flybys at Neptunian moons other than Triton  
844 are also possible.

845 The payload mass of  $\sim 70$  kg would be split between a number of scientific  
846 instruments, including (but not limited to) a narrow-angle camera, a wide-angle  
847 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

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856

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1243 Figure captions

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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 (Z<sub>1</sub>), 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.

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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



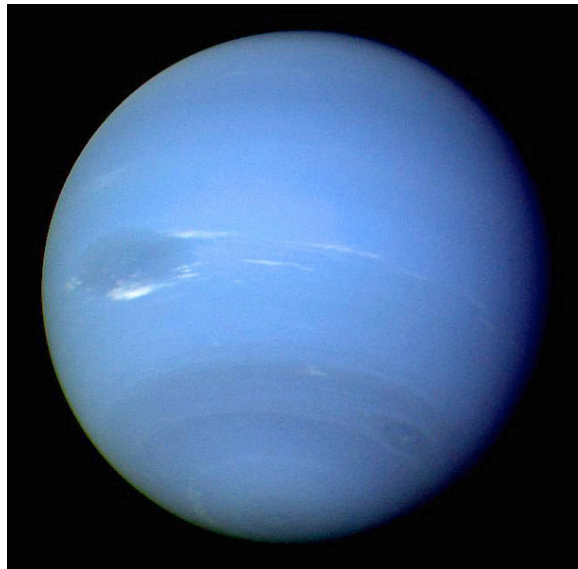
1292 represented by red arrows. (b) Example Neptune orbital tour, viewed from Neptune's  
1293 north pole.

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1296 Figures

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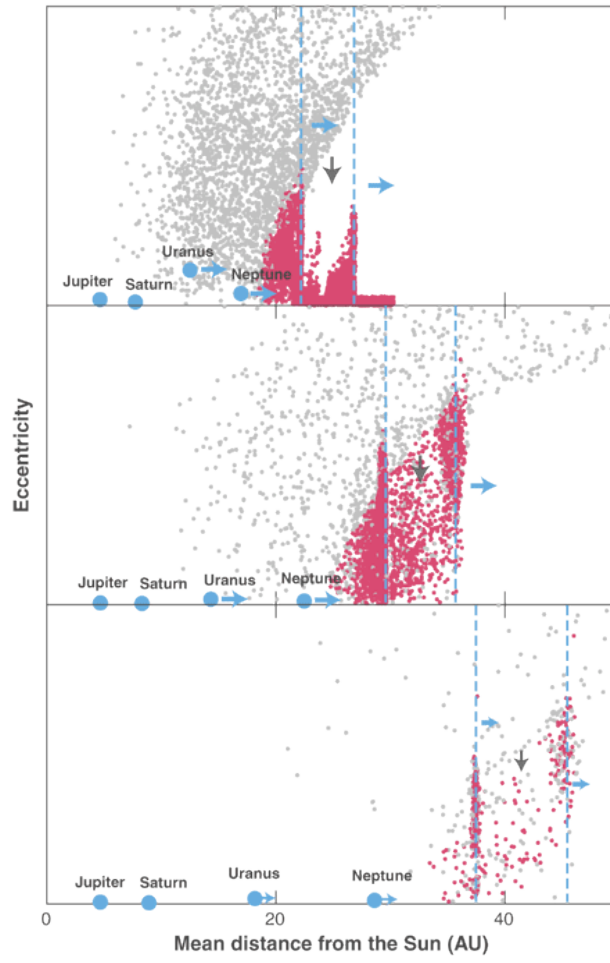


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1300 Figure 1.

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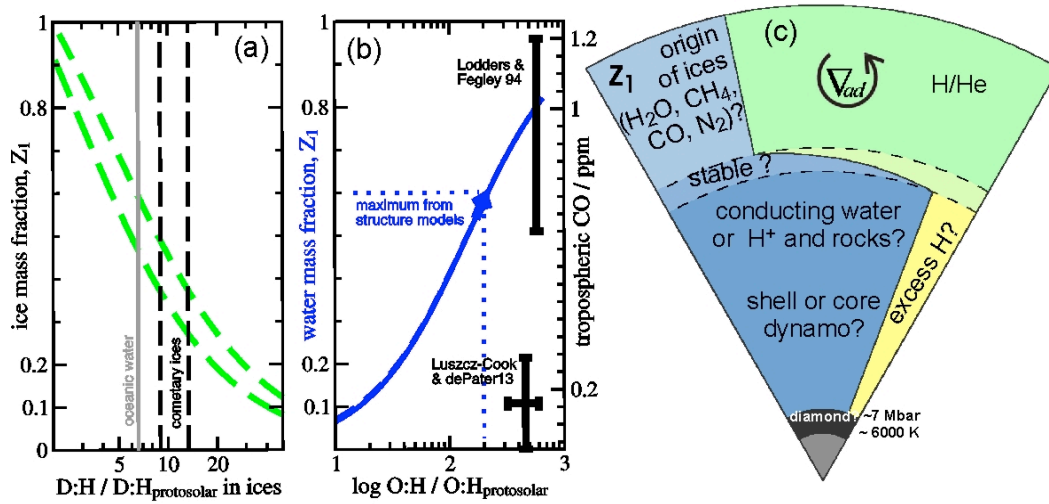


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1304 Figure 2.

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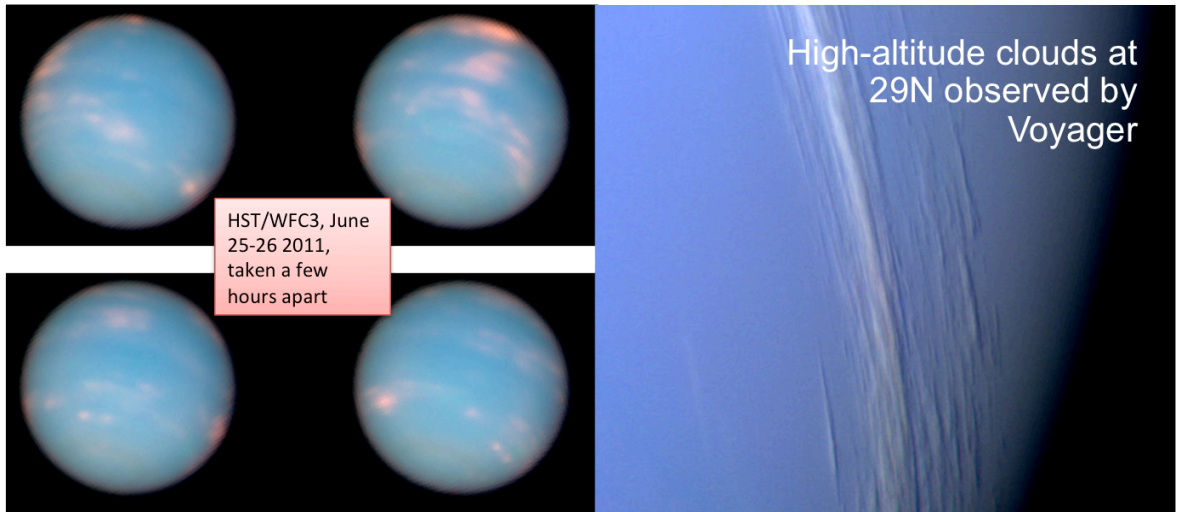


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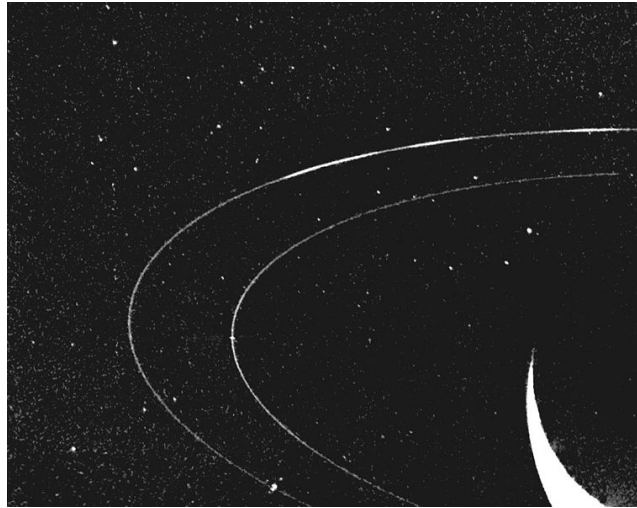
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1311 Figure 4.

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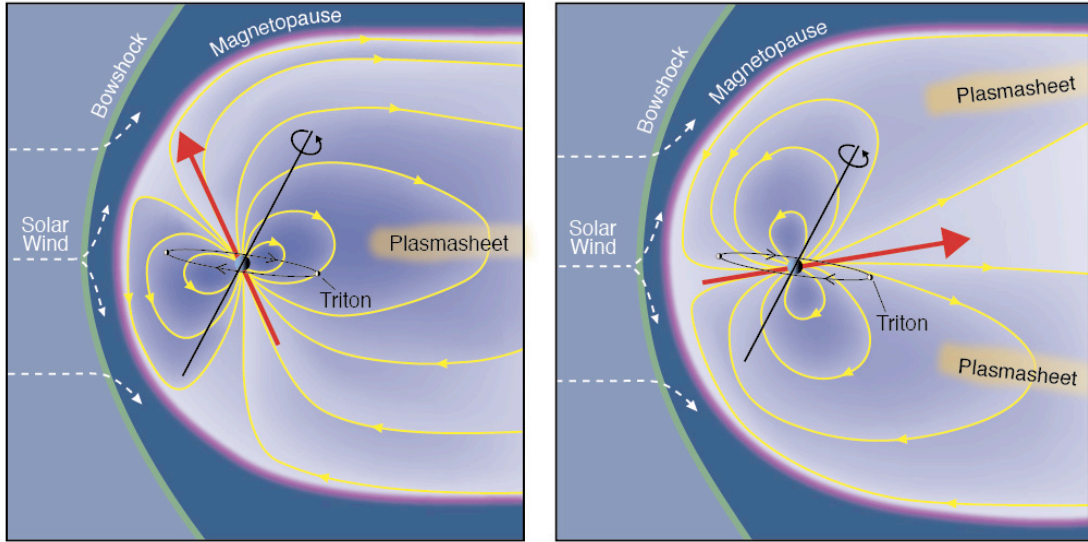


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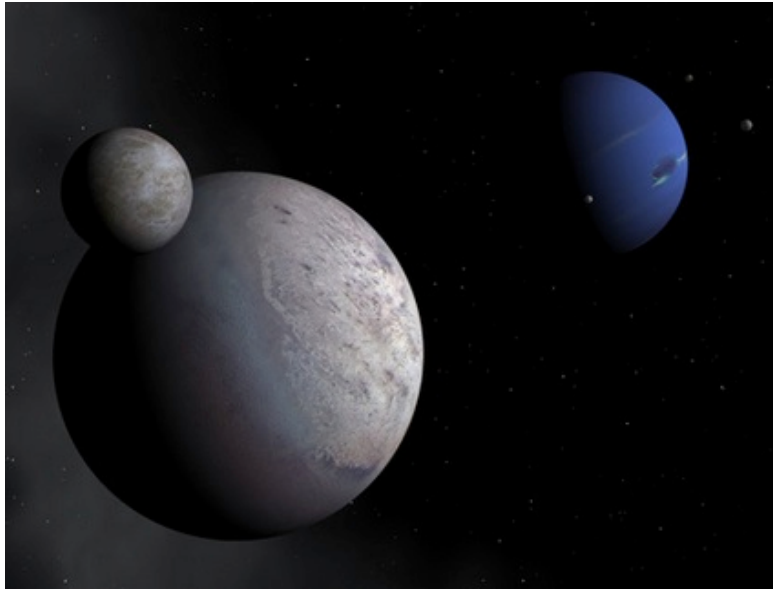
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1318 Figure 6.

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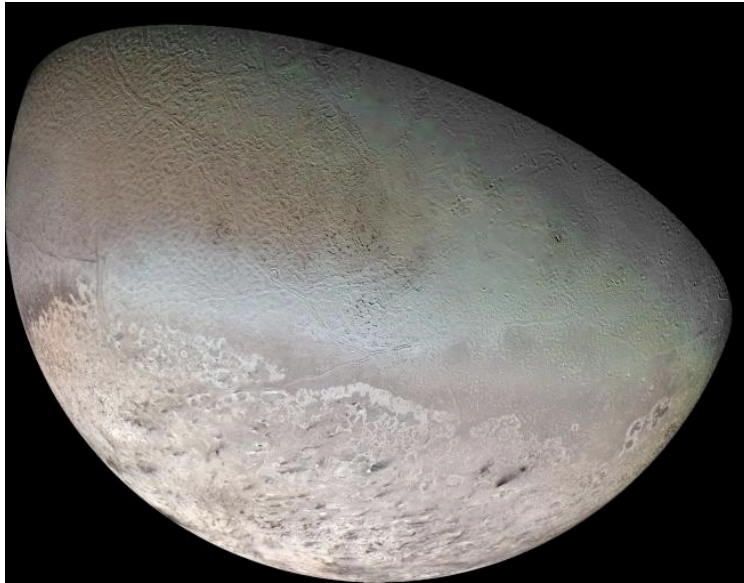
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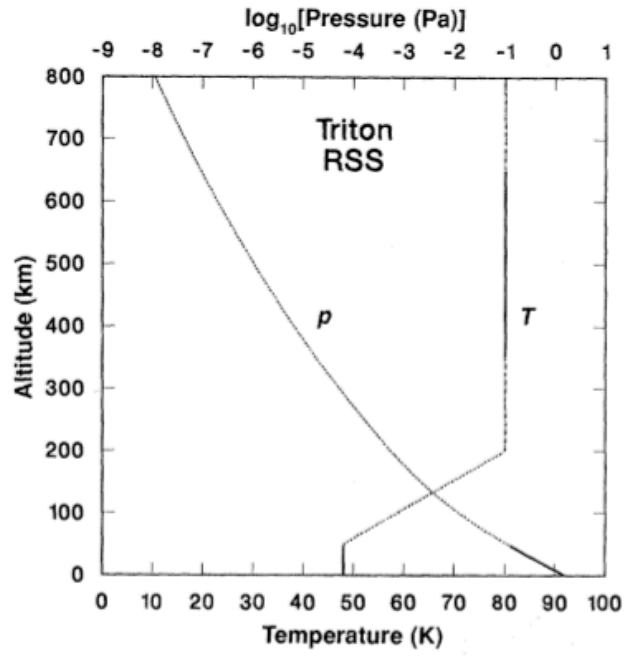


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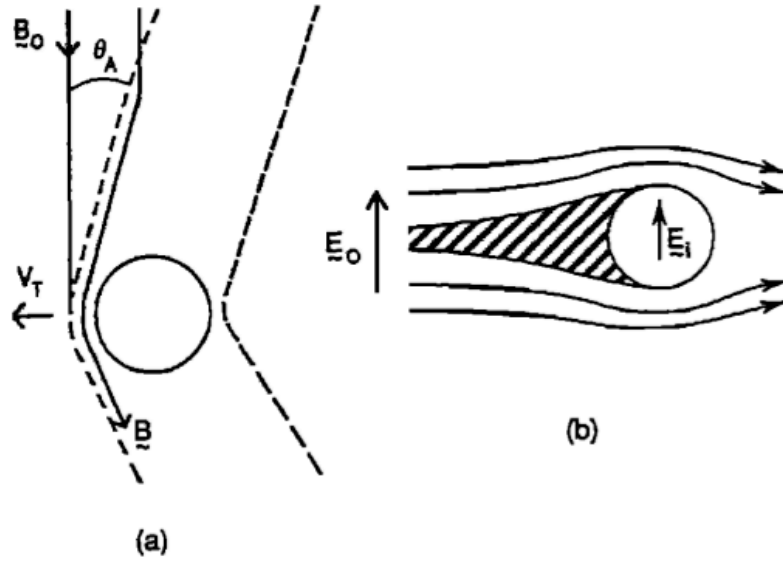
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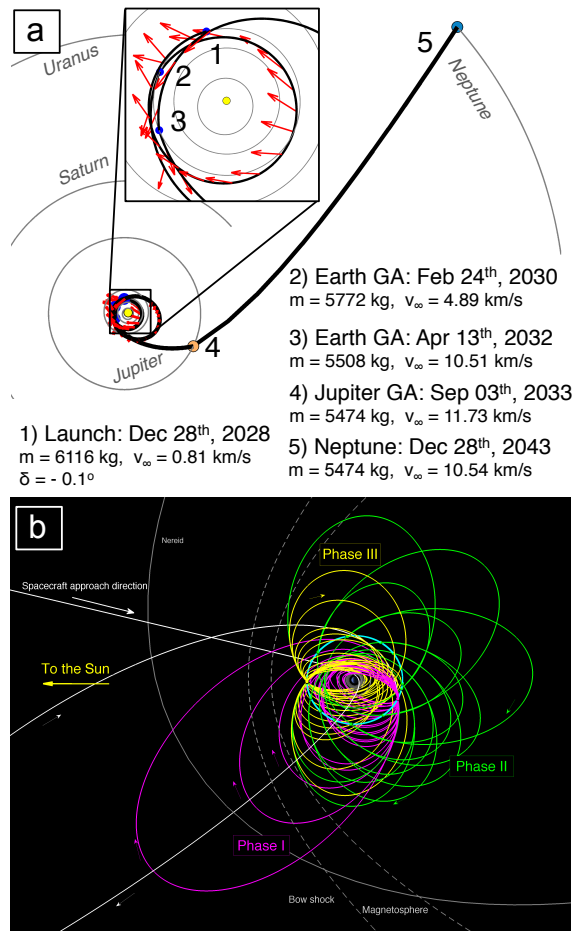
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1332 Figure 10.

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1336 Figure 11.

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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 <sup>-1</sup> .
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.