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Neptune Odyssey: A Flagship Concept for the Exploration of the Neptune–Triton System

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Abstract

The Neptune Odyssey mission concept is a Flagship-class orbiter and atmospheric probe to the Neptune–Triton system. This bold mission of exploration would orbit an ice-giant planet to study the planet, its rings, small satellites, space environment, and the planet-sized moon Triton. Triton is a captured dwarf planet from the Kuiper Belt, twin of Pluto, and likely ocean world. Odyssey addresses Neptune system-level science, with equal priorities placed on Neptune, its rings, moons, space environment, and Triton. Between Uranus and Neptune, the latter is unique in providing simultaneous access to both an ice giant and a Kuiper Belt dwarf planet. The spacecraft—in a class equivalent to the NASA/ESA/ASI Cassini spacecraft—would launch by 2031 on a Space Launch System or equivalent launch vehicle and utilize a Jupiter gravity assist for a 12 yr cruise to Neptune and a 4 yr prime orbital mission; alternatively a launch after 2031 would have a 16 yr direct-to-Neptune cruise phase. Our solution provides annual launch opportunities and allows for an easy upgrade to the shorter (12 yr) cruise. Odyssey would orbit Neptune retrograde (prograde with respect to Triton), using the moon's gravity to shape the orbital tour and allow coverage of Triton, Neptune, and the space environment. The atmospheric entry probe would descend in ∼37 minutes to the 10 bar pressure level in Neptune's atmosphere just before Odyssey's orbit-insertion engine burn. Odyssey's mission would end by conducting a Cassini-like "Grand Finale," passing inside the rings and ultimately taking a final great plunge into Neptune's atmosphere.

Key words: Extrasolar ice giants – Neptune – Neptunian satellites – Pluto – Uranus – Planetary magnetosphere – Van Allen radiation belt – Planetary surfaces – Surface ices – Ocean planets – Planetary rings – Planetary polar regions

1. Introduction: A Flagship Mission to the Neptune–Triton System

NASA has started preparations for the 2023 Planetary Science Decadal Survey, and one of the tasks of the 2023 Decadal Survey Committee will be to recommend a portfolio of planetary science missions. The Neptune–Triton mission described here and in full detail in Rymer et al. (2020a) was selected for study in 2019 and the final report provided to NASA in September 2020; as a consequence, much of the development of the mission concept was carried out during the global "lockdown" due to COVID-19. Large Strategic Missions, often referred to as "Flagship Missions," play a vital role in enabling the pursuit of the most compelling science questions, supporting workforce development, fostering international collaboration, providing opportunities for interdisciplinary investigations, and producing scientific discoveries that inspire the public and the next generations of scientists and engineers (National Academies of Sciences, Engineering, and Medicine 2016; Hammel 2020).

A Flagship Mission to Neptune and Triton would provide many firsts—an orbiter and atmospheric probe would be feasible on a Flagship budget and achievable given the current state of the technology required by such a venture (Rymer et al. 2020a—referred to heretofore as "the Odyssey report"). This bold mission of exploration would orbit Neptune to study the planet, its rings, small satellites, space environment, and the planet-sized moon Triton, itself a captured dwarf planet from the Kuiper Belt, twin of Pluto, and likely ocean world (e.g., Moore et al. 2015).

This mission concept has the working title "Neptune Odyssey." A family of instruments for both the orbiter and the probe has been identified, drawing from proven flight heritage designs. Broadly, the mission addresses the following questions: (1) How do the interiors and atmospheres of ice-giant (exo)planets form and evolve? (2) What causes Neptune's strange magnetic field, and how do its magnetosphere and aurora work? (3) Is Triton an ocean world? What causes its plumes? What is the nature of its atmosphere? (4) How can Triton's geophysics and composition expand our knowledge of dwarf planets like Pluto? (5) What are the connections between Neptune's rings, arcs, surface weathering, and small moons (some of which are captured from the Kuiper Belt or the protoplanetary disk)?

The instrument payload flows from these high-level science questions. A high-heritage visible/near-infrared (NIR) imager provides a human-eye-like view of Neptune, Triton, the small moons, etc., and education public outreach (EPO) cameras on both the orbiter and probe provide contextual images and a "you-are-there" perspective. A thermal infrared (IR) imager extends our viewing window farther into the infrared to understand the thermal properties of atmospheres, surfaces, and rings in this cold environment. Ultraviolet (UV) and visible/IR spectrometer construct spectra as a function of wavelength, vital for composition measurements, auroral observations, and deriving thermospheric temperatures. These are complemented by a laser altimeter that actively bounces light from the surface to create very accurate terrain readings. A microwave radiometer extends our exploration into the GHz range, enabling the study of contrasts in atmospheric composition within and below the clouds. Linking these, a radio receiver measures from the Hz to MHz range with multiple applications: ground truth of the in situ plasma density, remote sensing of moon activity, and lightning and spacecraft (SC) dust impacts. Two magnetometers on a deployable boom will construct maps of Neptune's magnetic field and (along with other instruments) determine whether Triton has a subsurface ocean. In situ measurements of neutral molecules (mass spectrometer), dust (dust detector), and charged particles up to several MeV (thermal plasma and high energy particle detectors) will determine the molecular and atomic composition near the spacecraft, thus providing observations of atmospheric composition and escape, the impact of the solar wind on Neptune's space environment, and the planet's radiation environment, as well as providing vital knowledge of the plasma pressure required to "correct" the magnetometer data. Finally, an energetic neutral atom (ENA) "imager" uses detected neutral atoms to construct all-sky images of Neptune and Triton's neutral clouds—a clever technique that was used to great effect at Saturn.

Neptune Odyssey is "shovel ready," with a concept maturity level of 4 (Wessen et al. 2013). That means we have defined the "Preferred Design Point: Point design to subsystem-level mass, power, performance, cost, risk" with a total modeled cost of less than \$3.4B (in fiscal year 2025 dollars, including 50% margin); this is a mission NASA could choose to stand up now without waiting for significant advances in technology. A Space Launch System (SLS) rocket with a Centaur upper stage (inside the fairing) allows direct-to-Neptune launch opportunities every calendar year. Our example spacecraft will launch with 3816 kg to Neptune orbit and utilize three radioisotope thermoelectric generators (RTGs), requiring 28.8 kg of plutonium. A Jupiter gravity assist (JGA) is available if we are ready for launch by 2031 and will reduce the cruise phase (providing the same mass to orbit) to 12 yr. If NASA selects a mission like Odyssey for a new start and an SLS-class vehicle is not available, then a Falcon Heavy-class vehicle could deliver the same payload mass using a solar electric propulsion (SEP) kick stage.

From the start of this long mission, preserving knowledge and cultural continuity should be a priority. Observations along the way (for example, stereo observations of the edges of our heliosphere, asteroid and Centaur flybys, and using Odyssey's cameras for a rear-view look back at our solar system) would sustain stakeholder interest and provide unprecedented opportunities for discovery (Cohen & Rymer 2020). Finally, equipping both the orbiter and probe with cameras specially purposed for public engagement helps to share the joy of exploration and discovery with those who help make space exploration possible—the general public.

This article draws on the study report, as well as subsequent discussions and presentations, to describe the science goals, strawman payload, launch opportunities, and power requirements to make this mission a reality in the next decade. Sections 2–6 describe the science goals aligned with the science traceability matrix provided in the Odyssey report: Section 2, Neptune the Ice-giant Planet; Section 3, Auroral and Magnetospheric Connections; Section 4, Neptune's Strange Magnetic Field and Magnetospheric Processes; Section 5, Small Satellites and Ring Systems; and Section 6, Triton as an Ocean World and Triton as a Kuiper Belt Dwarf Planet. Section 7 describes opportunities to increase science return by exploiting the excellent payload and trajectory for science that applies to other NASA divisions. Section 8 places the mission in the appropriate political context, elucidating on the benefits

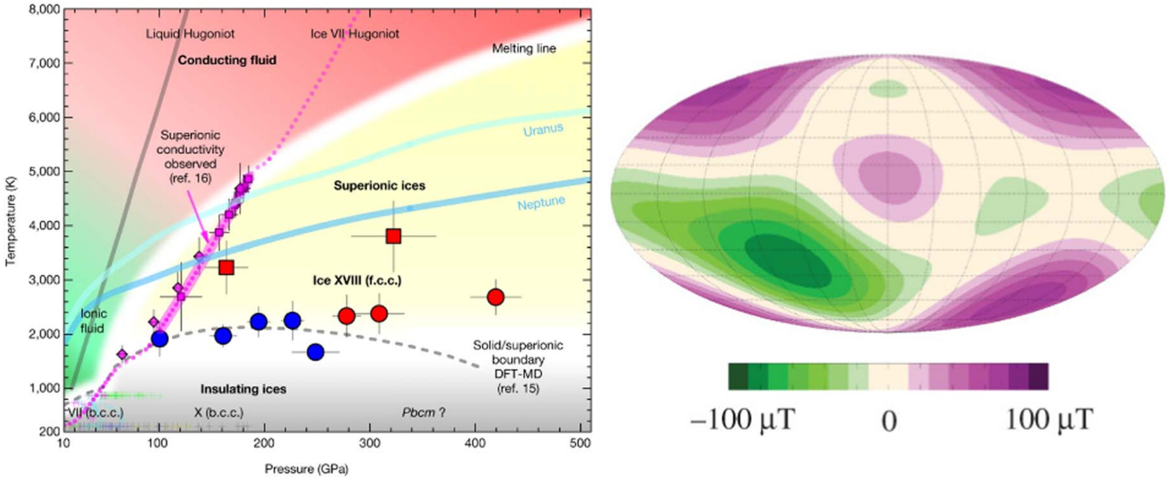

Figure 1. Left: phase diagram of water showing hypothesized interior conditions for the ice-giant (Millot et al. 2019) magnetic fields, which are likely generated in the relatively shallow ionic fluid region. Right: radial magnetic field at the 1 bar pressure level as measured by Voyager 2, including dipole, quadrupole, and octupole components (Holme & Bloxham 1996; Schubert & Soderlund 2011) with purple (green) denoting outward (inward) directed fields.

of Flagship missions in general to NASA and the NASA workforce and the benefits of the scope of this mission in particular as "a mission for everyone." Section 9 describes some techniques we and other missions have identified that are necessary to ensure the success of long-duration missions. Section 10 contains a brief summary of the technical details for the mission, with a focus on payload, trajectory, and launch opportunities and an assessment of fuel necessary for the estimated three Next-Gen radioisotope power supplies (NGRTGs) required. Finally, Section 11 provides a summary and concluding remarks.

2. Neptune the Ice-giant Planet

Major revelations of the structure and mechanics of the interiors of Jupiter and Saturn from Juno and the Cassini Grand Finale, respectively, are a stark contrast to our ignorance of ice-giant interiors (e.g., Cao et al. 2020; Soderlund & Stanley 2020; Stevenson 2020). While it has long been assumed that the ice giants are water dominated, this has been called into question with the potential that these planets may instead be "rock giants" (Helled & Fortney 2020; Teanby et al. 2020). Thus, measurements of interior structure and composition are of prime importance; see Figure 1. The Odyssey mission's exploration of the planet Neptune will address overarching goals to understand the planet's origin and how it evolved and to place it in context with other planets.

The dynamics and chemistry of a planetary atmosphere are inextricably linked with the thermal structure, which controls which species condense and where, the efficiency of chemical reactions, the nature of instabilities and convective processes, and the 3D shear on atmospheric flows. Each of these processes also feeds back to shape the temperature structure but are currently poorly constrained for Neptune (e.g., Dahl et al. 2021). The dominant feature of Neptune's visible-wavelength "photosphere" is its global system of jet streams that have a westward (i.e., retrograde to planetary rotation) peak at the equator and an eastward peak in each of the north/south hemispheres (Fletcher et al. 2020). This structure is similar to Uranus and in stark contrast to Jupiter and Saturn. This dichotomy in the giant-planet atmospheric dynamics remains one of the biggest fundamental questions to be answered in geophysical fluid dynamics, which Odyssey will help resolve.

Where, when, and how did Neptune form and migrate in the solar system? The single most important measurement to understand the formation of Neptune is the bulk abundance of noble gases and their isotopic ratios, as well as the isotopic ratios of hydrogen, oxygen, carbon, and nitrogen (e.g., Atreya et al. 2020; Mandt et al. 2020). Odyssey achieves this with mass spectrometer measurements made from an in situ atmospheric probe with supporting atmospheric pressure, temperature, and helium abundance data down to a pressure of 10 bar. Complementary remote-sensing observations will provide critical context for the interpretation of these probe measurements. Furthermore, Odyssey will make gravity and magnetometer measurements to determine its internal density structure and the location and nature of its magnetic-field-generating dynamo, providing clues as to its interior structure and constraining formation models (e.g., Helled & Fortney 2020). Odyssey could also search for normal-mode oscillations of the planet by using its high-resolution cameras to look for periodic perturbations to the rings. If detected, these oscillations would provide a direct probe of the interior structure and be a powerful technique if it can be demonstrated (e.g., Mankovich 2020 for Saturn). Similarly, the global energy balance of Neptune is also critical to understand its internal structure, both at present and over time (e.g., Helled & Fortney 2020).

What processes govern the dynamics, chemistry, and evolution of ice-giant atmospheres and interior? The thermal evolution of Neptune is central to understanding the planet's overall evolution and the driving forces of interior and atmospheric dynamics. Odyssey's suite of remote-sensing instruments will determine how much internal heat is being released in the present epoch, constraining processes such as the rain out of carbon and atmospheric convection. Neptune's dynamo will be characterized in detail during low-periapse flybys. The same instruments can locally map where sunlight is deposited and where internal energy is released to indicate how internal dynamics distribute the incoming and outgoing energy. Vigorous convection and meridional circulation patterns also inform how internal dynamics distribute energy (e.g. Fletcher et al. 2020). Such patterns are identified by tracking clouds with visible and NIR cameras, or the distribution of condensable or disequilibrium gases using a microwave sounder and IR spectrometer, or secular variation from magnetometer measurements. Gravity and magnetic field measurements near Neptune will also determine how deep the zonal winds extend into the planet and whether they interact with the dynamo (Kaspi et al. 2013; Soyuer et al. 2020). The planet's internal rotation rate will be refined primarily by a radio wave detector, which will also search for auroral footprints and lightning.

Neptune exhibits various types of observable changes beyond those associated with thermal evolution, and the timescales of these changes vary from hours to decades. The changes are manifested by, for example, variations in zonal wind speeds, cloud/haze distribution, photochemical production of stratospheric hydrocarbons (Moses et al. 2018, 2020), the gas abundance of condensable species, and formation and dissipation of the famous "Dark Spots" and associated orographic clouds (see review by Hueso & Sanchez-Lavega 2019). To understand the role of various processes that drive these present-day phenomena (e.g., cloud microphysics, cumulus convection, atmospheric turbulence, radiative transfer/forcing, photochemistry, seasonally varying insolation), the Odyssey orbiter is equipped with a suite of remote-sensing instruments. Imaging cameras will record the global distribution of clouds and hazes to determine their vertical layering via radiative transfer models. Cloud-tracking measurements will reveal the turbulent wind field. UV, visible, IR spectrographs and the microwave radiometer will determine the three-dimensional distribution of various chemical species, such as disequilibrium species, to infer the meridional circulation and vertical mixing.

Odyssey's suite of remote-sensing spectrometers will provide information on the composition and chemistry of the observable atmosphere by identifying the abundance and distribution of various species in the stratosphere and troposphere, as well as determining temperature profiles. This information not only provides clues about circulation patterns, as mentioned above, but also informs about the potential infall of material from the rings and/or the interplanetary environment, and—via chemical modeling—the bulk composition of the planet.

As the Galileo probe did for Jupiter, the Odyssey atmospheric probe provides a single-point ground truth for all of the "processes" measurements discussed here. Its determination of temperature, composition, net flux, winds, and the hydrogen ortho-para ratio provide validation and a calibration point for all remote-sensing observations. Only one giant-planet entry probe has been achieved in the 60+ yr of planetary exploration. We will double that count, using instruments much more capable than the 1970s technology available to the Galileo probe at Jupiter.

How do ice giants differ from gas giants and super-Earths? By understanding the formation and evolution of Neptune and the present-day processes acting upon it, we gain insights into our own and other planetary systems (e.g., Wakeford & Dalba 2020). For example, identification of key physical processes such as planetary migration and moist convection in thick H_2/He atmospheres would not have stemmed from Earth studies alone. By utilizing Neptune as a natural laboratory, we will learn about, and be better able to characterize, planetary types that may not exist in our solar system (e.g., super-Earths and sub-Neptunes); see Figure 2.

Potential Science Questions—Neptune:

1. How do giant planets form and evolve?
2. What is Neptune's internal structure and what regions are adiabatic?
3. Why does Neptune have a multipolar, nonaxisymmetric magnetic field?
4. Why is Neptune's ratio of emitted/received energy larger than for any other planet?
5. What are the thermal structure, composition, and 3D circulation of Neptune's atmosphere?

Suggested Measurement Objectives:

1. Measure noble gases and isotopic ratios
2. Define magnetic and gravity field models, and assess temporal variability
3. Establish the energy balance and distribution of internal heat flux
4. Create temperature maps as a function of depth
5. Map distribution of tropospheric volatiles, stratospheric hydrocarbons, and oxygen species
6. Map clouds and haze
7. Measure the wind field in high resolution

3. Auroral and Magnetospheric Connections

Neptune's Strange Magnetic Field and Magnetospheric Processes. Neptune's multipolar intrinsic magnetic field has no clear symmetries along any axis, and no information about secular variation is known at present (e.g., Holme & Bloxham 1996). Although a convection-driven dynamo is widely agreed upon as the source of this field, the underlying reason why it is nondipolar and nonaxisymmetric remains poorly understood (Soderlund & Stanley 2020). Neptune's magnetosphere is complex, with significant nondipolar contributions, tilt, and offset from the planet's center (Paty et al. 2020). These peculiarities, combined with Neptune's relatively rapid rotational period, lead to widely varying configurations on diurnal and seasonal timescales. In particular, this dynamic behavior tests many precepts in the understanding of planetary magnetospheres. The case of Neptune is made even more intriguing by the presence of the captured dwarf planet Triton, a satellite slightly larger than Pluto with a collisional atmosphere that might be an active ocean world. The study of Neptune's aurora and mapping its magnetic field is vital to understanding processes critical to the Neptune system. It is also essential to our exploration of Triton, both in understanding Triton's interactions with Neptune's magnetosphere, as well as investigating the magnetic environment of the icy moon itself. Understanding this interaction, via studies of Triton's auroral activity and magnetic induction using magnetic sounding techniques, will help reveal whether the moon contains a subsurface.

What is the configuration of Neptune's intrinsic magnetic field and how does the dynamo operate? A pair of boom-mounted fluxgate magnetometers will make continuous vector measurements of Neptune's magnetic field with sufficient temporal resolution and sensitivity to probe the intrinsic magnetic field of Neptune and will also investigate magnetospheric currents and dynamics. The Odyssey tour is designed to provide full coverage of Neptune's magnetic environment and will provide the first detailed investigations of an ice-giant dynamo and magnetosphere. In order to determine the location and convective dynamics of the dynamo, the bulk composition, internal structure, global energy balance, interior circulations, and internal energy fluxes must also be investigated as described above.

How is the Neptunian magnetospheric current system configured? The magnetospheric investigations benefit from the planet's large dipole tilt and rapid rotation, which allows a

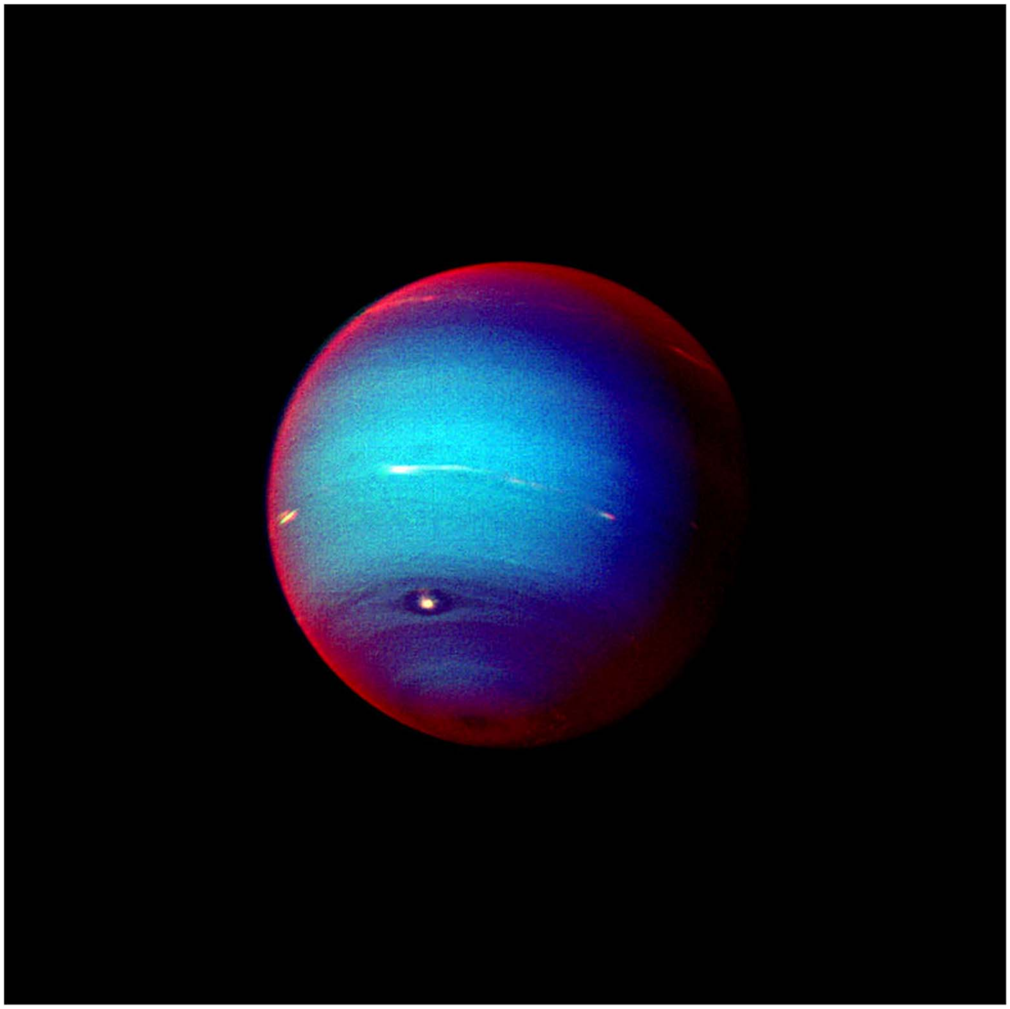

Figure 2. Last image of Neptune taken by Voyager 2 shown in enhanced color. Near the edge of the planet, the haze scatters sunlight at higher altitude, above most of the methane, causing the bright red edge around the planet. Figure courtesy of NASA.

spacecraft in a given orbital plane to sample a large range of magnetic latitudes over diurnal timescales. Precession of the Odyssey orbit over the duration of the baseline mission enables comprehensive coverage of all magnetic local times, with multiple chances to investigate solar wind coupling on the day side and plasma transport processes in the night-side magnetotail.

How is plasma sourced, transported, and lost within the Neptunian magnetosphere? Can Neptune develop and sustain significant radiation belts? What drives the aurora? Neptune's magnetosphere was observed to contain heavy ions, and it has been suggested that these might be nitrogen coming from Triton—possibly from a neutral torus sourced from Triton. However, given the apparent quiescence of the system, how that torus may be formed and how the resulting particles are transported remain unclear. The Odyssey payload includes a comprehensive plasma suite (including measurements of ions and electrons across a continuous energy range from <10 eV to >10 MeV) mounted to provide 4π sr coverage. Together, this suite will provide energy, angular, and mass species distributions of particle populations throughout the magnetosphere to address particle transport processes, identify magnetospheric sources and losses, characterize the radiation belts, and investigate auroral drivers. A radio and plasma wave sensor with three antennas is also included to probe waves from a few hertz to 2 MHz, allowing investigation of both magnetospheric wave–particle interactions and auroral radio emissions. The tour's comprehensive coverage of much of the middle and outer magnetosphere as well as the lower-periapsis orbits (<10 RN) also allows for sampling of the planet's radiation belts, which largely reside within Triton's orbit (14 RN).

It is unknown how Neptune's complex magnetic topology and interactions with the solar wind will influence the structure and location of the planet's auroral emissions. Voyager 2 observed very faint aurora on the dark side of Neptune, but no additional detections of aurora at Neptune have been possible from Earth, in contrast to the irregular auroral bright spot detections at Uranus (Lamy 2020). It is also unclear what a potential auroral footprint from Triton might look like, given that the moon's orbit is highly inclined relative to the planet's rotational and magnetic axes. Auroral studies are enabled on Odyssey through a combination of remote-sensing and in situ instruments.

Voyager 2 did not include any NIR instrument so crucial measurements in that wavelength range (such as H_3^+) remain to be made; see also Stallard et al. (2021) and Kollmann et al. (2020) for more details on aurora and magnetospheric measurements.

Potential Science Questions—Aurora and Magnetosphere Connections:

1. What is the detailed configuration of Neptune's intrinsic magnetic field?
2. What dynamic processes drive energy and mass transport in Neptune's magnetosphere?
3. How are the radiation belts sourced, and what processes determine their structure and energy spectrum?
4. How do auroral currents flow into and through the ionosphere at Neptune?
5. Why is Neptune's exosphere so hot?

Suggested Measurement Objectives:

1. Measure magnetospheric plasma sources and losses and characterize the planetary radiation belts.
2. Measure the energy, angular, and compositional distributions of thermal and energetic plasma versus location and their variability with time.
3. Measure the vector magnetic field and the power and spectrum of electromagnetic waves versus location and their variability with time.
4. Generate a global magnetosphere model including magnetospheric current systems.
5. Image the H and H_2 (UV, Vis) and H_3^+ (IR) auroral and ENA emissions.
6. Monitor and characterize auroral activity.

4. Small Satellites and Ring Systems

Little is understood about the strikingly different ring and satellite systems around Neptune as compared to the relatively well-studied Saturn system. Neptune's complex ring dynamics, including the apparent stability of some ring arcs harbored within expansive dusty rings, presents particularly intriguing questions about particle interactions and dynamics with direct applications to circumstellar disks. Using ring systems as laboratories for planetary formation processes was a high-priority goal for establishing ground truth for exoplanets from giant-planet studies in the 2013 Visions and Voyages Decadal Survey, and we advocate for this to be maintained in the coming decades with particular emphasis on expanding our understanding of ring dynamics by studying the disrupted Neptunian ring system.

The inner regular satellites may have formed with Neptune, such that their composition could indicate available source materials for the planet. The rings, primarily micron-sized dust (Porco et al. 1995), must be replenished constantly, likely via collisions and/or meteorite impacts on the unobserved "parent" bodies of the rings, as dust has a relatively short lifetime. Ring arcs embedded within the outer Adams ring have been observed to change in brightness, drift in position, or vanish completely (de Pater et al. 2005, 2018). The arcs' stability and confinement are still areas of active research, with solar radiation forces and inelastic particle collisions challenging their maintenance through resonances or co-orbital moonlets (Fortya & Sicardy 1996; Hanninen & Porco 1997). (Note that even Saturn's main rings may be young, possibly not more than ~150 Myr old; Zhang et al. 2017). We need to identify the sources of the rings in order to understand their formation through a search for as yet undiscovered moons. The rings can also capture information about Neptune's interior through waves generated in the rings by resonances with the planet's normal modes (Hedman & Nicholson 2013).

Some of the irregular moons may be captured objects (Holman et al. 2004) or remnants of the primordial satellite system perturbed into more complex orbits during the capture of Triton, as is hypothesized for Nereid (Goldreich et al. 1989; Brown et al. 1991; Thomas et al. 1995; Rufu & Canup 2017). Compositional analyses would assist in constraining the origins of the satellites. Of particular interest would be the composition and morphology of recently-discovered Hippocamp, which may be a fragment of the larger, nearby moon Proteus (Showalter et al. 2019); see also Hsu et al. (2021) and Brooks et al. (2021).

What are the connections between Neptune's rings, arcs, surface weathering, and small moons? How does the current ring–moon system operate? The most striking component of the complex ring–moon system is a set of ring arcs embedded within the outer Adams ring, as mentioned above. The current position of the LeVerrier ring is still unexplained, and the sources of the dust-sized particles that dominate the entire ring system have not been identified. Many aspects of Neptune's dynamical environment, including the potential role of the planet itself, still need to be explored. To address these questions, Odyssey will use a high-resolution visible camera to do the following: (1) perform a comprehensive search at all longitudes of rings and arcs and at both low ($<60°$) and high ($>140°$) phase angles for small moonlets (>100 m) that could be source bodies for ring material, as well as additional ring and ring structures that could reveal the physical processes operating in this system; (2) take multiple high-resolution looks at the rings in order to identify the role of both outside forces and internal processes, supported by UV and/or NIR stellar occultation's ring structure measurements; and (3) make precise measurements of the small moons' positions to quantify their mutual interactions and perturbations from other bodies.

What are the origin and evolution of the rings and small moons? Neptune's rings and small moons are thought to be remnants of the material present before Triton was captured. Hence, the composition of these bodies can provide information about the solid material that surrounded Neptune when it formed. Unlike the Saturn system, several of the moons are interior to the corotation of the planet, meaning they should move inward until they are tidally disrupted. These bodies could therefore have cycled between being moons and rings multiple times. The small moon Hippocamp, discovered in 2004 (Showalter et al. 2019), may be a fragment knocked off of the larger moon Proteus. The history and evolution of the rings and small moons are therefore complex and require further investigation. Odyssey would probe the origins and evolution of the rings and small moons by doing the following: (1) Use a suite of spectrometers from the UV to the NIR at low ($<70°$) phase angles to measure the composition of the material that forms the rings and moons. Odyssey's proximal orbits would enable spatially resolved images (<1 km pix^{-1} resolution) on the leading and trailing hemispheres of the known satellites. These reflectance measurements would be compared with Triton to assess how the material initially surrounding Neptune differs from that in the Kuiper Belt. (2) Take advantage of the close moon flybys to take high-resolution images to map the geological structures on the moons. Radio science measurements of their bulk physical parameters would constrain their bulk composition and geological history. (3) Measure the size

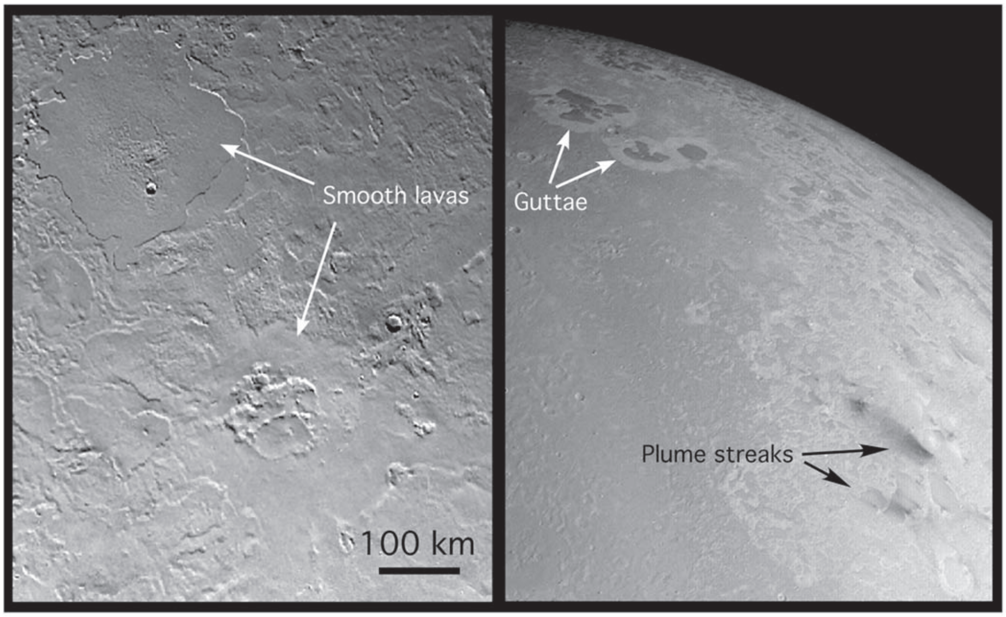

Figure 3. Triton's candidate cryovolcanic features include smooth lavas (left), and guttae and plume streaks (right). Images courtesy of NASA/JPL (Quick & Prockter 2013).

distribution of the ring particles through high phase angle (>140°) photometry and through UV and/or NIR stellar occultation observations, which are sensitive to ring particles as small as a few micrometers, in order to ascertain their evolutionary timescales. (4) Repeat images of the same ring longitudes and moon positions to search for slow variations in the moons' and rings' orbits due to tidal interactions with the planet that could reveal how the system evolved into its current state. (5) Study distant satellites of Neptune, especially those that orbit retrograde and are likely captured Kuiper Belt objects. The study of these satellites from the UV to NIR can further our understanding of the composition and geology of other small worlds beyond Neptune. Such insight on small Kuiper Belt objects could yield information on early solar system formation and dynamics.

Science Questions—Rings and Satellites:

1. What are the origin and evolution of the rings and small satellites?
2. How does the current ring–moon system operate and sustain ring arcs?

Suggested Measurement Objectives:

1. Search for embedded moonlets
2. Identify influences from resonances with satellites and the planet in the rings
3. Observe short-term and long-term variations in the rings and ring arcs
4. Determine particle-size distribution of the rings
5. Constrain photometric properties of the rings and moons

5. Triton as an Ocean World

Triton's Interior Structure. Does Triton have a subsurface liquid ocean? Recent studies have considered the effects of tidal dissipation in Triton and have found that both solid-body tides and obliquity tides may lead to the preservation of a subsurface ocean until the present day (Gaeman et al. 2012; Chen et al. 2014; Nimmo & Spencer 2015). Based on evidence for Triton's young surface (10–100 MY) as observed by the Voyager spacecraft (Schenck & Zahnle 2007) and the possibility of ocean-derived activity, similar to that observed by Cassini at Enceladus, NASA's Roadmap to Ocean Worlds (ROW) team identified Triton as the highest priority "candidate ocean world" target and specifically called out the significance of a mission study to resolve Triton's ocean world status (Hendrix et al. 2019, 2021).

Triton Surface Geology and Geophysics. What are the geologic processes responsible for Triton's unique surface features? Although the specific composition of Triton's crustal material is unknown, the surface is punctuated with ridges, cliffs, and knobs that extend as high as 1 km above the surface and by numerous unrelaxed, ∼1.5 km deep impact craters. The extent of the surface topography suggests that the crust is composed of rigid materials such as water ice, ammonia-water ice, CO_2, and/or SO_2, all of which are strong enough to preserve high-standing topography at Triton's surface temperatures.

Triton's Atmosphere and Ionosphere. Are Triton's plumes endogenic or solar driven? Recent data and models motivate a reexamination of the source of Triton's plumes; see Figure 3 (Hansen et al. 2018). The Cassini discovery of tidally driven eruptions confined geographically on Enceladus, and measurements such as vapor mass flux and exit speeds, have expanded possible scenarios for Triton. The possibility that Triton's plumes could be endogenic and sourced from subsurface liquid is deserving of further investigation and would solidify Triton's identity as an ocean world. Additional questions that would further our understanding of Triton and its atmosphere, include the following: How does Triton's atmosphere respond to seasonal redistribution of volatiles? What is the nature of Triton's global circulation and climatic response? How does the highly conducting Triton ionosphere interact with the corotating magnetosphere of Neptune? How is Triton's extremely strong ionosphere generated and maintained, and are magnetospheric interactions key?

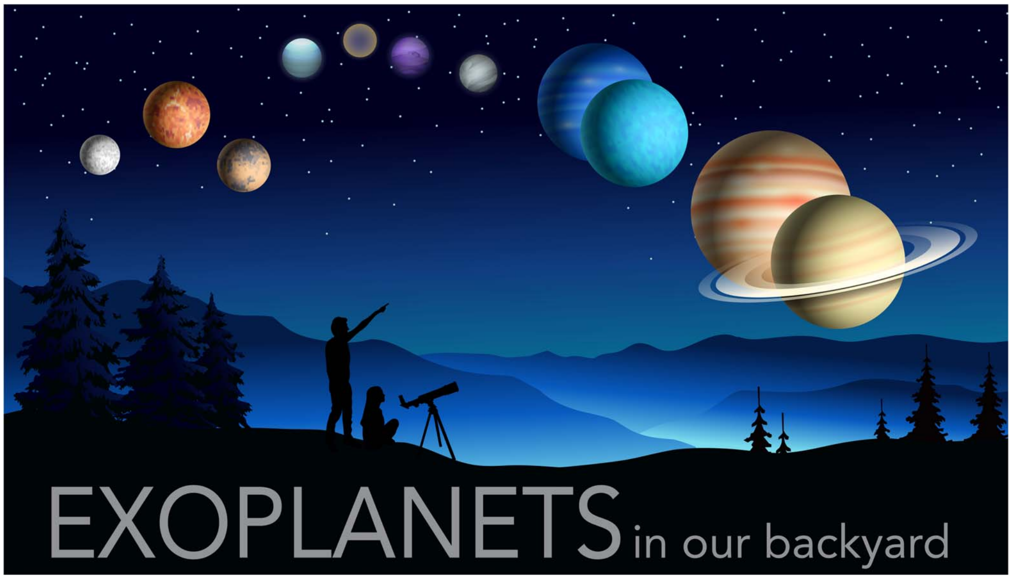

Figure 4. Logo for the cross-assessment group workshop "Exoplanets in our Backyard," January 2020 see Arney et al. (2021).

6. Triton as a Kuiper Belt Dwarf Planet: Comparative Planetology

It has long been recognized (Harrington & Flandern 1979; Smith et al. 1989; McKinnon & Kirk 2007) that Triton, being in a retrograde orbit around Neptune, is almost certainly a captured planet from the Kuiper Belt. Astonishingly, Triton's mass and diameter are slightly larger than any known dwarf planet currently in the Kuiper Belt: 2707 km versus 2377 km for Pluto and 2330 km for Eris, and only slightly smaller than Europa's 3122 km (see also Hansen et al. 2021).

When a population of planets has been studied to some sufficient level of detail, similarities and differences become apparent between them. Comparing and contrasting these attributes is the basis of the discipline of comparative planetology. Because Triton is a captured Kuiper Belt dwarf planet, its attributes can be tested against Pluto and Charon, and as spacecraft visit more dwarf planets, with those worlds as well. See also Runyon et al. (2021).

However, owing to the vast population of $>$100 dwarf planets (diameters $>$ 400 km) in the Kuiper Belt, their extreme distances of several tens of astronomical units (and beyond 900 au in the case of Sedna) and the very long travel times necessary to reach them, it is unlikely we will see missions to more Kuiper Belt dwarf planets in the foreseeable future. Thus, Triton, as a dwarf planet orbiting a giant planet, is the most accessible Kuiper Belt dwarf planet that would represent and advance the comparative planetology of this population. The following paragraph lists related questions Odyssey could address.

How and why is Triton's geology and geophysics different from Pluto and Charon? How do Triton's isotopic ratios compare to Neptune and Uranus, Kuiper Belt objects, comets, and other dwarf planets? And how did the capture of Triton impact its bulk composition and interior structure compared to dwarf planets elsewhere in the Kuiper Belt? These questions can be addressed in tandem while studying Triton as a candidate ocean world using the instruments listed in Table 2.

Science Questions—Triton:

1. Is there an ocean present, and if so, what are its depth and salinity?
2. How thick is the ice shell?
3. What generates the plumes?
4. What seasonal factors influence Triton's atmosphere, and how are they manifested?
5. How are Triton's surface–atmosphere–magnetosphere coupled?
6. How and why are Triton's geology and geophysics different from Pluto and Charon?
7. How do Triton's isotopic ratios compare to Neptune and Uranus, Kuiper Belt objects, comets, and other dwarf planets?
8. How did the capture of Triton impact its bulk composition and interior structure compared to dwarf planets elsewhere in the Kuiper Belt?

Suggested Measurement Objectives:

1. Measure Triton's induced or intrinsic magnetic field and search for temporal variations
2. Measure Triton's gravity field
3. Measure changes in landforms, plumes, flexure
4. Map plumes and plume activity
5. Map distribution of Triton surface ices
6. Detect and measure scale heights of atmospheric condensed ices, hydrocarbons and N2
7. Compute energy input into Triton

7. Cross-disciplinary Science Opportunities: Exoplanets and Cruise-phase Science

A mission of such broad scope easily crosses disciplinary and NASA Divisional goals. Here we outline the science that this mission could do in addition to the planetary science goals of the prime mission.

Neptune as an exoplanet. The last several years of exoplanet discovery have taught us that Neptune-sized planets are very common in our galaxy; it is therefore desirable to better understand this class of planets (see review in Wakeford & Dalba 2020). Importantly, the formation of ice giants remains an open question in the fields of planetary science and astrophysics (e.g., Pollack et al. 1996; Helled & Fortney 2020).

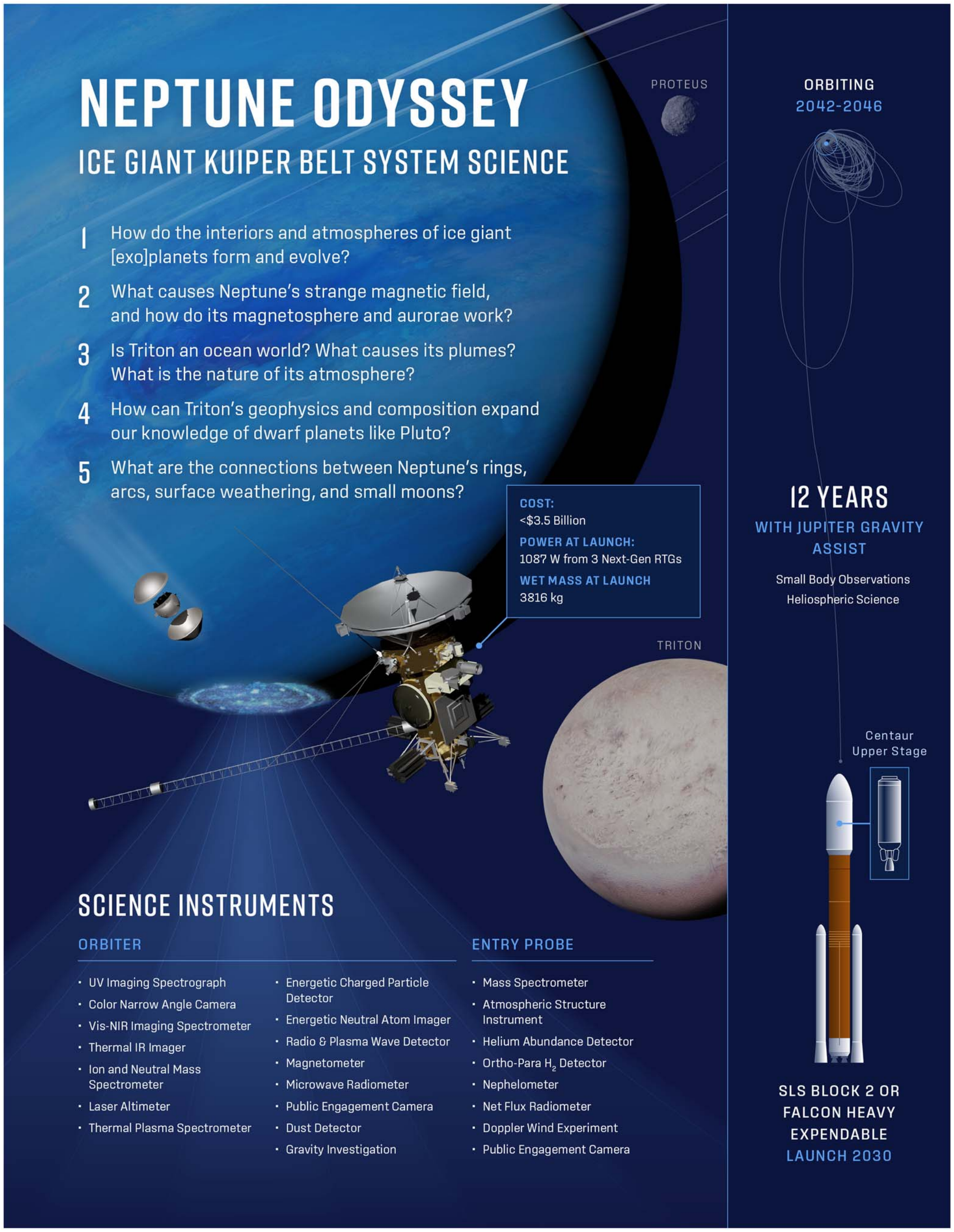

Figure 5. Neptune Odyssey fact sheet for a “direct-to-Neptune” scenario.

Solar System planets; exoplanets in our backyard. An imaging suite for a Neptune mission, from UV to thermal IR, would provide the capabilities needed for transformational observations of solar system planets on the 12 to 16 yr cruise phase to Neptune. Disk-averaged observations are crucial to understanding how our solar system's planets would be viewed “as exoplanets” by a distant observer; see Figure 4 (see also Arney et al. 2021; Fortney et al. 2021; Harman et al. 2021).

Heliospheric observations. Comprehensive particle and field instruments, optimized for Neptune, would enable solar wind studies and monitoring of the outer solar system. Data from an ENA imager during cruise and near apoapse during the nominal tour could provide ENA maps of the heliosphere/interstellar medium (ISM) boundary (e.g., Cohen & Rymer 2020).

Centaur/asteroid flyby. A comprehensive remote-sensing suite would also be ideal for making a flyby of a Centaur en route to Neptune. Distant, opportunistic Centaur observations would allow measurements of light curves and composition maps (Singer et al. 2019). A bonus encounter with a Jovian trojan asteroid to supplement the Lucy mission may also be possible, depending on the launch opportunity.

8. The Importance of Flagship Missions to Solar System Exploration

A balanced portfolio of small (Discovery), medium (New Frontiers), and large strategic-class missions is important for NASA (National Academies of Sciences, Engineering, and Medicine 2016). Small- and medium-sized missions enable a faster cadence and responsivity to new discoveries and have higher

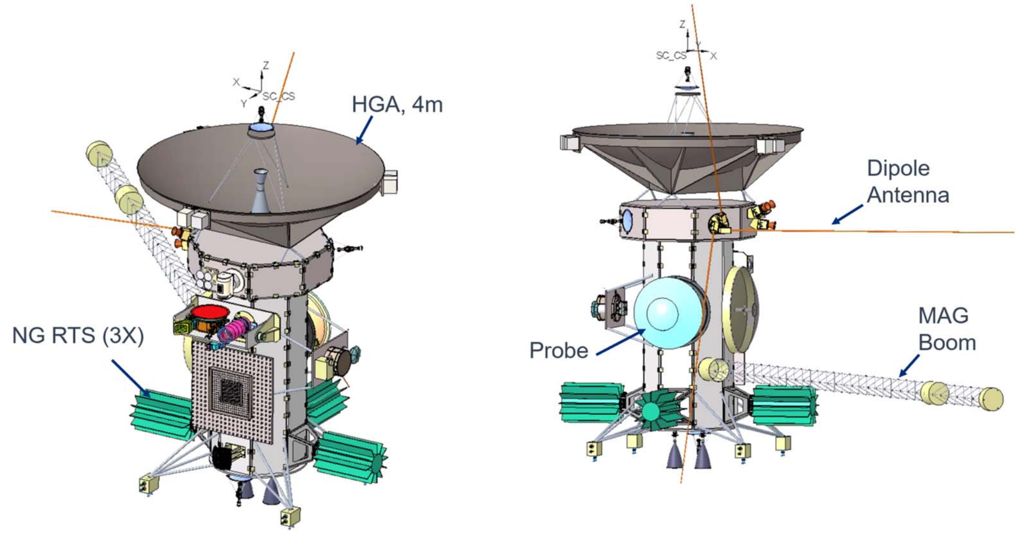

Figure 6. Odyssey and payload schematics.

risk tolerances. They also require a narrower scientific focus, with one or a few tightly interconnected goals and a limited payload of instruments. Unlike small- and medium-scale missions, the scale and cost of flagship missions enable and should require coverage of a broad suite of science objectives, engaging with a large cross section of the planetary community. For this reason, a mission to Neptune and Triton is ideal for a NASA flagship. The research described above encompasses planetary interiors, atmospheres, evolution, magnetospheres, rings, small satellites, ocean worlds, Kuiper Belt objects, heliophysics, and exoplanets. The long duration of the mission will provide opportunities for engagement with scientists from across these fields, as well as training for the next generation of diversely motivated mission scientists, reflecting the growth and evolution of the planetary community.

A flagship mission to study the Neptune and Triton system provides unique opportunities to interact with scientists from across the planetary community, as well as across disciplines. One strong value-added aspect of the long-duration, well-instrumented, and directed nature of flagship missions is the ability to onboard several rounds of new co-investigators via Participating Scientist programs. Participating Scientist programs have been demonstrated to be of critical importance and value to the Planetary Science Division by increasing intellectual diversity among a project science team and enhancing the science return of the mission (Prockter et al. 2021). They also provide important career experience, training, and networking opportunities for participants, especially those in the early stages of their careers. A perhaps less-obvious finding of the above-referenced study was that "Participating Scientist programs also enhance demographic diversity among teams, and are seen as a valuable opportunity for many in the community who may not otherwise have access to mission participation." Hence, it is especially important that flagship missions engage with a large cross section of research areas, so that Participating Scientist programs can have the greatest impact and that planetary scientists across the community can have the opportunity to benefit from the training, interactions, networking, and career experience. The Neptune–Triton flagship mission would provide a diverse suite of science objects, engaging with a broad cross section of the planetary community and additionally offering the benefits Participating Scientist positions to scientists in a wide range of disciplines.

Table 1
Mission Design Table

Orbit Parameters (Apogee, Perigee, Inclination, etc.)	Value	Units
Mission lifetime	240	months
Total orbiter mass with contingency (includes instruments)	1594	kg
Total probe mass with contingency (includes instruments)	274	kg
Propellant mass without contingency	1910	kg
Propellant contingency	2	%
Propellant mass with contingency	1948	kg
Launch adapter[a] mass with contingency	106	kg
Total launch mass (maximum expected value (MEV) dry and propellant masses)	3816	kg
Launch vehicle	SLS Block 2	type
Launch vehicle lift capability (including adapter)	4852	kg
Launch vehicle mass margin (using MEV dry and propellant masses)	1036	kg
Launch vehicle mass margin (%)	21	%

Note.
[a] The launch vehicle adapter is the structure that goes between the upper stage of the launch vehicle and the launch vehicle/space vehicle separation system. Because the launch vehicle adapter is chosen by the mission (there are a number of options ranging in capability and interface type), its mass is chargeable to the launch vehicle performance.

9. Human Factors for Long-duration Space Missions

Space exploration is a team effort, and missions require a plan for managing interactions over a multidecadal span. The literature on the science of teams, leadership, and collaboration provides a series of best practices and insights into the human element of scientific collaborations. The Planetary Science community can draw upon lessons learned from past missions, especially Cassini, to identify ways to meet three significant challenges on the human scale for future outer

Table 2
Neptune Odyssey Orbiter Instrument Payload (Includes Mission/Instrument Heritage, TRL, Mass, Power, and Cost)

	Measurement Range	Heritage Mission/Instrument	TRL	Mass with Contingency (kg)	Power with Contingency (W)	Cost in FY25 $M (+15% cf. FY20)
Magnetometer	Range ±1530 to ±51,300 nT Resolution 0.047–1.6 nT	MESSENGER/Mag	>6	4.70 (including boom)	5.80	7.1
Color Narrow-angle Camera	350–850 nm, ∼20 channels	Lucy/L'LORRI & New Horizons/LORRI	6[a]	9.90	5.75	17.5[a]
UV Imaging Spectrograph	465–1881 Å	New Horizons/Alice	>6	5.00	5.75	15.1
Ion and Neutral Mass Spectrometer	1–99 Da 100–1,000,000 channels	Cassini/INMS	>6	10.60	26.80	43.2
Laser Altimeter	1 064.5 nm	MESSENGER/MLA	>6	8.50	28.75	21.8
Vis-NIR Imaging Spectrometer	0.4–0.975 μm, 6 channels 1.0–5.0 μm, 1472 channels	Lucy/L'Ralph &New Horizons/Ralph	6[a]	35.65	27.60	60.6
Radio and Plasma Wave Detector	18 channels/decade Electric few Hz–20 MHz Magnetic few Hz–20 kHz	Juno/Waves	>6	14.60	9.32	10.3
Thermal Infrared Imager	0.35–400 μm, 9 channels	LRO/Diviner	>6	11.50	18.40	29.3
Microwave Radiometer	0.6–22 GHz, 6 channels	Juno/MWR	6	52.90	36.80	56.4
Thermal Plasma Spectrometer	Ions 0.01–46.2 keV 1–50 amu Energy Res. 28%–18% Mass Res. 2.5–11 Electrons 0.1–95 keV Energy Res: 10.4%–13.2%	Juno/JADE	>6	14.71	3.35	35.8
Energetic Charged Particle Detector	Ions 20 keV–15 MeV Electrons 25–1000 keV	Parker Solar Probe/EPI-Lo	>6	3.91	4.31	15.5
Energetic Neutral Atom Imager	Neutrals 3–300 keV Ions 5 MeV Electrons 30–700 keV	IMAP/Ultra	6[a]	8.20[a]	7.60[a]	25.8[a]
Dust Detector	1–500 amu ⩾200 m/Δm	IMAP/IDEX	6[a]	13.28[a]	15.27[a]	15.1[a]
EPO Camera	400–900 nm, 3 channels	Rosetta/CIVA	>6	0.80	2.30	1.9

Note.
[a] CBE = Current Best Estimate.

solar system missions (e.g., Neptune, Pluto, Interstellar Probe) these aspects also apply to other missions and should be shared accordingly.

Data Stewardship. Prior studies of long-term projects demonstrate significant hurdles in data management, including establishing standards, maintaining compatibility, and instrumental health.

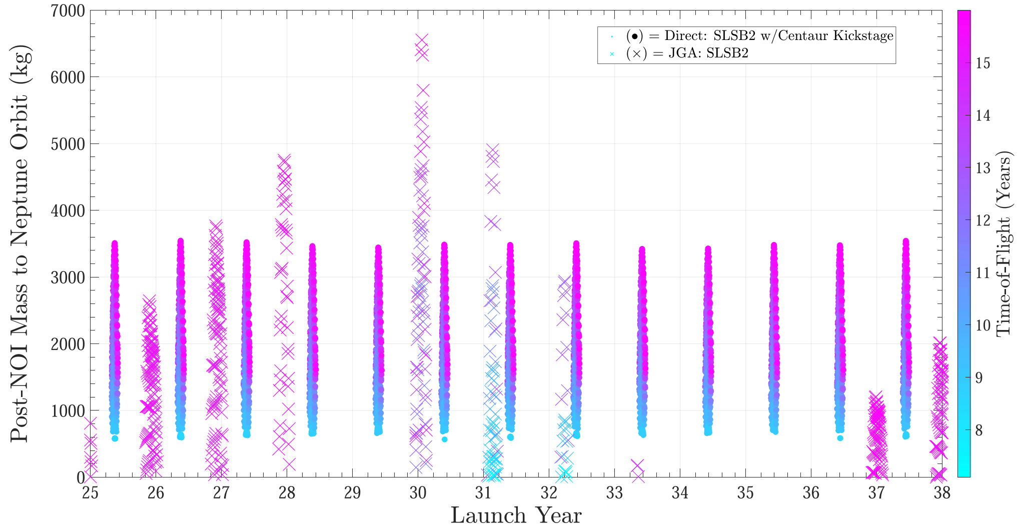

Figure 7. Earth–Neptune transfer orbits with time of flight (TOF) less than 16 yr. Direct Earth–Neptune (EN) launch options (assuming SLSB1B with a Centaur upper stage) are indicated by dots and Earth–Jupiter–Neptune (EJN) launch options are indicated by crosses. The symbols are color-coded, corresponding to time from launch to arrival at Neptune (from 7 to 16 yr), as shown by the color bar.

Table 3
Neptune Odyssey Probe Instrument Payload (Includes Mission/Instrument Heritage, TRL, Mass, Power, and Cost)

	Heritage Mission/Instrument	TRL	Mass with Contingency (kg)	Power with Contingency (W)	Cost in FY25 $M (+15% cf. FY20)
Mass Spectrometer	Galileo Probe/MS; Cassini–Huygens	9	16.90	28.75	22.4
Atmospheric Structure Instrument	SNAP Study/ASI; Cassini–Huygens/HASI	6	1.82	5.75	5.6
Helium Abundance Detector	Galileo Probe/HAD	9	1.82	1.00	3.5
Ortho-para H_2 Detector	Ice-giant SDT	6	0.65	4.00	4.4
Nephelometer	Galileo Probe/Nephelometer	9	2.99	5.29	7.1
Net Flux Radiometer	Galileo Probe/Net Flux Radiometer	9	4.07	4.60	8.2
Doppler Wind Experiment	Huygens Probe/DWE	9	0.43	1.40	
Public Engagement Camera	Rosetta/Philae	9	0.78	2.30	2.8

We advocate for the deliberate development (and funding) of techniques to

1. Produce robust, long-term plans for data stewardship, with clear expectations shared across the instrumentation suite (Bietz & Lee 2009);
2. Share data in ways consistent with the operational considerations of the mission (Vertesi & Dourish 2011);
3. Produce a local database that feeds the archive pipeline with quick-view products available for establishing cross instrumental partnerships (Birnholtz et al. 2009); and
4. Fund stewardship, compatibility, and process responsibilities, making data work a valued part of the investigation (Lee et al. 2006).

Planning for the Long Term. From mission formulation through development and cruise, it will take well over a decade for this mission to reach Neptune. As well as adopting cross-divisional science during the cruise phase, we advocate for the deliberate development (and funding) of techniques to

1. Adopt a bureaucratic-hierarchical form (Weber 1968), consistent with the Flagship organizational style that best permits multigenerational leadership and team participation and turnover. Such social forms are more likely to support women and minorities in advancement (Freeman 1972; Smith-Doerr 2004) and to support the encyclopedic data collection expected of Flagship missions (J. Vertesi, in press).
2. Include a plan for multigenerational leadership. For example, each instrument team could nurture more than one deputy PI to develop to share the experience and skill set necessary for leadership (Linde 2001).

International Partnership. Missions of this scale and scope benefit tremendously from international partners, both in terms of scientific expertise and fiscal support. For Neptune, for example, advanced discussions exist, e.g., *Workshop on In Situ Exploration of the Ice Giants*, Marseille, France, 2019 January; and *Future exploration of the ice giants*, London Royal Society, 2020 January; and a just-completed ESA-led study (http://sci.esa.int/future-missions-department/61307-cdf-study-report-ice-giants/) found that an ESA-provided entry probe is the most technologically mature and least expensive option for ESA participation in a NASA-led ice-giant mission. European interest in partnership missions to the ice giants is exemplified by the recent proposals to ESA's long-

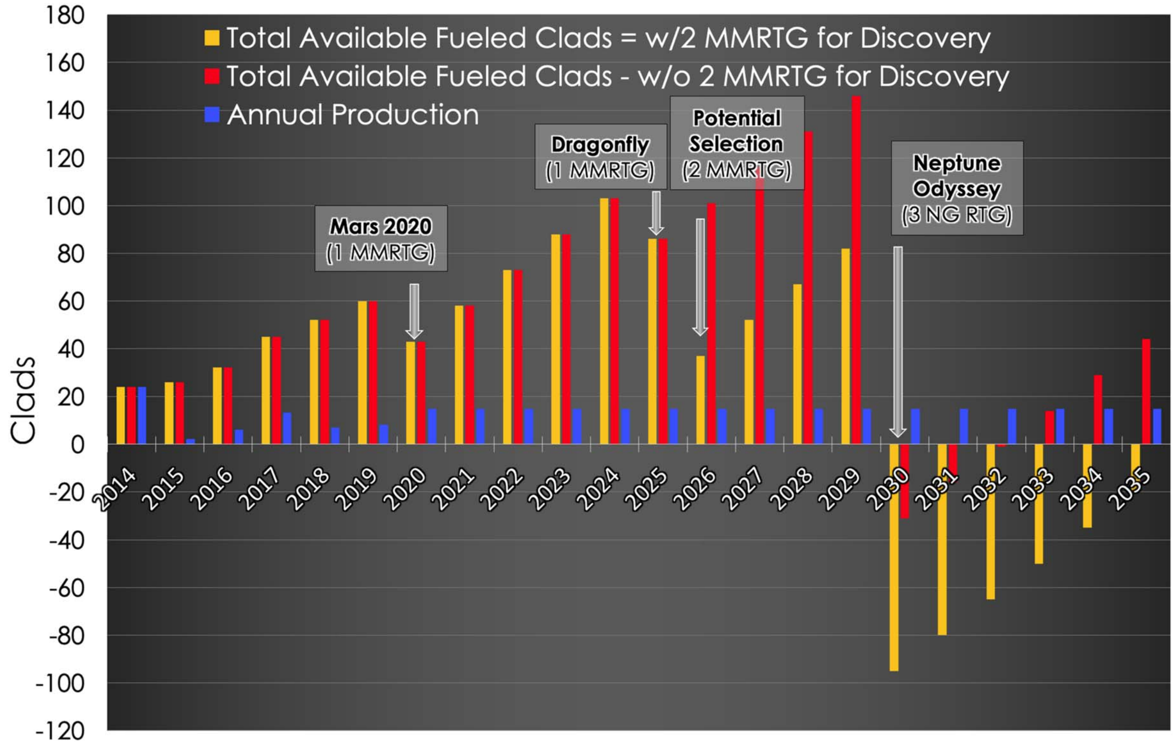

Figure 8. Number of fuel clads available (y-axis) vs. year assuming continued production of 15 clads per year. Adapted from Zakrajsek (2019).

term strategic planning exercise, known as Voyage 2050 (Fletcher et al. 2020). International partnerships can be difficult to sustain due to the pressures of institutional and national requirements as well as cultural differences (Sheehan 2007). Study of the extraordinarily successful Cassini mission demonstrates this is best managed through relational work at the level of the mission scientists and technical teams (Groen & Hampden-Turner 2005), We advocate for the deliberate development (and funding) of techniques to manage this challenge.

10. The Technology for an Ice-giant Flagship is Ready

For complete details of a shovel-ready Neptune–Triton mission, we refer readers to the PMCS report *Neptune Odyssey: Mission to the Neptune–Triton System* (Rymer et al. 2020a). We also refer readers to the OPAG White Paper (Moore et al. 2021), which indicates the high priority for a Neptune Flagship mission start in the coming decade, and others describing high-level goals (Masters et al. 2014; Hofstadter et al. 2017; Blanc et al. 2021; Guillot et al. 2021).

A fact sheet providing the mission-vital statistics for the annual direct-to-Neptune launch opportunity is provided in Figure 5. Odyssey would orbit Neptune, using Triton flybys to alter the spacecraft's orbit around Neptune and applying a similar mission architecture to Cassini–Huygens. Odyssey would collect data and images at a wide range of altitudes and orbital inclinations and would explore other Neptunian moons and rings. This study focused on using annual direct-to-Neptune launch opportunities, the development of a trajectory that supports the use of both an orbiter and a probe, and an example tour that demonstrates the ability to collect and downlink the observation data to meet the mission goals (Table 1). The study was completed by an integrated team of scientists and engineers from a variety of organizations.

The instruments included in the payload (Tables 2 and 3) for the study are all based on previously flown instruments that may not represent state of the art but would allow the mission to be flown now without technology development. All of the mission components are at technical readiness level (TRL) $\geqslant$ 6. It is anticipated that there will be technological advances that continue to improve the TRL levels beyond the existing levels.

The flight system consists of the Neptune Odyssey spacecraft with the accommodated Neptune probe. The spacecraft enters the Neptune–Triton system after a long cruise, plane-change maneuver, probe deployment, and Neptune Orbit-insertion (NOI) burn.

Several trades were conducted to evaluate the launch vehicle, launch opportunities, and mass delivered to Neptune. The Neptune–Odyssey mission has chosen to use an SLS Block 2 launch vehicle (LV) with a Centaur kick stage. This option gives Neptune Odyssey the greatest flexibility in mass, volume, and launch opportunity. The mission design team looked at the launch opportunities with and without a JGA. Requiring a JGA limits launch opportunities prior to 2031. Thus, we costed a version that can launch direct-to-Neptune annually and chose 2033 as our launch year as that launch date was (by a small amount) the most mass constrained. Pivoting to a 2031 launch would be straightforward and would enable much shorter cruise durations, as illustrated in Figure 7. The trade determined that using a kick stage or SEP with a different LV provided the equivalent of the energy gained through the JGA, so SEP could easily be substituted for the kick stage. If an option to employ SEP is chosen, a different LV could be used. The spacecraft design could accommodate the use of SEP within mass, power, and propellant budgets, but fairing volume could be a constraint.

We optimized the power required for the mission by, for example, the thermal coupling of the flight system and using a large high gain antenna. Odyssey as currently configured requires three Next-Generation RTGs (NGRTGs); each NGRTG comprises 16 GPHS-RTGs (General Purpose Heat Source RTGs), requiring 28.8 kg of plutonium in total. Figure 8 (derived from Zakrajsek 2019) shows that the current production rate of 15 clads per year is insufficient to fuel the Odyssey mission as designed. After Mars 2020, the total fuel clad needs represented in Figure 8 are Dragonfly (32 clads), potential Discovery-2019 (up to 64 clads), and Neptune Odyssey (192 clads) for a total of up to 288 clads (of which 224 are for Dragonfly and Odyssey). In 2020, after fueling Mars 2020 (Perseverance), the US had 43 fuel clads left available for future missions (Zakrajsek 2019), and continuing the 15 clads-per-year production between 2021 and 2030 would produce an additional 150 clads to make 193 clads available for missions in that timeframe. Thus, the current production rate of 15 clads per year is insufficient to supply enough clads to fuel the three NextGen RTGs incorporated in the Odyssey design in 2030.

Increasing the production rate of the plutonium clads is critical to fuel the RTGs needed for Odyssey by 2030. The current production facilities are capable of producing up to ∼22 clads per year (Zakrajsek et al. 2021). If the production rate is increased to 22 clads per year in 2026 and subsequent years, 228 clads could be made available to fuel missions in the 2021–2030 timeframe, which would be sufficient to fuel Dragonfly and Odyssey. Although delaying Odyssey's launch readiness date would add time to produce the fuel clads and alleviate the need to increase the production rate, delaying the launch is undesirable because Jupiter is available for gravity assist to reach Neptune only if the mission is launched by 2031. Although reaching Neptune is possible without a Jupiter flyby, such a trajectory would add up to 5 yr to the cruise, during which the RTG performance degrades, and reduces the science return of the mission by making less power available for the instruments after Neptune arrival.

11. Summary

Following decades of exploration of nearly all the other planets in our solar system, we have the instrumentation and expertise necessary to successfully explore the Neptune–Triton system. Here we have provided the science case, philosophical motivation, and technological blueprint to make it a reality, the preceding sections describe:

1. Neptune the Ice-giant Planet. How do the interiors and atmospheres of ice-giant (exo)planets form and evolve?
2. Auroral and Magnetospheric Connections. Neptune's Strange Magnetic Field and Magnetospheric Processes. What causes Neptune's strange magnetic field, and how do its magnetosphere and aurora work?
3. Small Satellites and Ring Systems. What are the origins of and connections between Neptune's rings, arcs, surface weathering, and small moons?
4. Triton as an Ocean World. Is Triton an ocean world? What causes its plumes? What is the nature of its atmosphere?
5. Triton as a Kuiper Belt Dwarf Planet: Comparative Planetology. How can Triton's geology, geophysics, and composition expand our knowledge of dwarf planets like Pluto?
6. Cross-disciplinary Science Opportunities: Exoplanets and Cruise Phase Science
7. The Importance of Flagship Missions to Solar System Exploration
8. Human Factors for Long-duration Space Missions
9. Technology for an Ice-giant Flagship. The technology is ready and the timing is now.

We have not revisited an ice giant since our initial passing glimpse with Voyager 2 over 30 yr ago; it was a mission that inspired curiosity in multiple generations of scientists and planetary enthusiasts alike, and Neptune and Triton beckon us to return and explore. We are ready.

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