Neptune Orbital Survey and TRitOn MissiOn

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Abstract

Neptune Orbital Survey and TRitOn MissiOn (NOSTROMO) is a large-class exploration mission to the Neptunian system with a focus on Neptune and its main moon Triton. The mission aims to increase our understanding of the formation and evolution of Neptune, which plays a key role in the formation of our Solar System. Within the Solar System, Neptune serves as the best analogue for one of the dominant class of exoplanets detected to date. The study of its moon Triton could reveal substantial information regarding the formation of icy dwarf planets in the outer Solar system, and may provide new perspectives on habitability in the outer Solar System.

1 Introduction

By exploring the Neptunian system, the Neptune Orbital Survey and TRitOn MissiOn (NOSTROMO) aims to enhance our understanding of planetary formation and evolution, both within our Solar System and beyond. As stated in the ESA Voyage 2050 long-term science plan; a mission to the ice giants and their moons is a necessary step in the exploration of the Solar System. Furthermore, Fulton and Petigura, 2018 show that a significant fraction of exoplanets discovered to date are Neptune-like in their atmosphere and size. By studying Neptune, we gain insights into the processes that shaped not only the giant planets but also the myriad of exoplanets discovered in recent years. By studying its moon Triton, a potential Kuiper Belt object, we aim to gain a better understanding of how captured bodies evolve and interact with their parent planets. Furthermore, investigating Triton could will light on its potential habitability and its role in the context of the Solar System's formation and evolution.

1.1 Scientific background

1.1.1 Neptune

Formation It is postulated that Neptune formed via planetesimal accumulation initially at ∼12 astronomical units (AU) and then migrated to its current orbit at around 30 AU (Gomes et al., 2005). As Neptune did not accrete as much gas as Jupiter and Saturn, it is assumed that its core reached completion at later stages of the Solar nebula evolution, when the gas density was low. Giant impacts influenced Neptune's evolution but less significantly than Uranus'. Neptune's obliquity of $\sim 28°$ (about 20% greater than Earth's) and its heat flux ratio of 2.61 (the highest in the Solar System) contrasts sharply with Uranus's obliquity of 98° and nearly unitary heat flux ratio ("Encyclopedia of Planetary Science" 1997). This suggests the two ice giants have experienced totally different collisional histories (Morbidelli et al., 2012).

Atmosphere & Internal structure Highly unexplored, the Neptunian system has only been visited once during a flyby of the Voyager 2 probe in 1989. Flyby data, combined with ground- and space-based telescope observations have revealed that Neptune has the most meteorologically active atmosphere in our Solar System, despite its great distance from the Sun. Its zonal wind configuration shows prograde/retrograde motions along with the fastest zonal velocities (up to 600 m/s) measured in any planetary atmosphere (Ingersoll, 1990). Studies suggests that the atmosphere of Neptune is predominantly composed of at least 80% hydrogen and a smaller portion of helium, $\sim 20\%$ (Berenguer and Katsonis, n.d.). The internal structure of Neptune is still poorly understood, but some hypothesizes were formulated based on the masses, radii, and gravitational fields data collected by Voyager 2 (Smith, Soderblom, Beebe, et al., 1986; Smith, Soderblom, Banfield, et al., 1989); the central inner core of Neptune is believed to be composed of a mixture of rocks and ice (Hubbard et al., 1991).

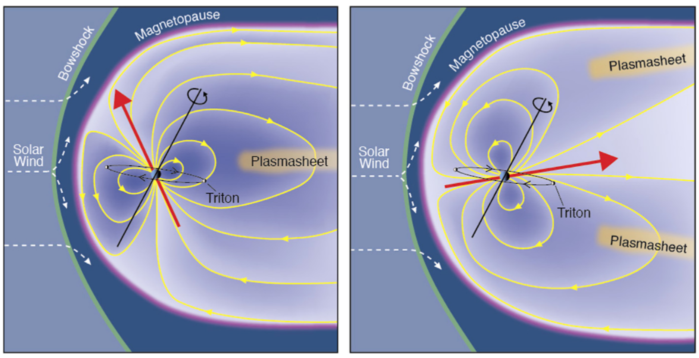

Figure 1: Changing configuration of Neptune's magnetosphere. Source: Masters et al., 2014. Image credit: Fran Bagenal and Steve Bartlett

Magnetosphere The Voyager 2 flyby provided limited data on Neptune's magnetospheric system (Fig. 1) but revealed several key features. The angle between the magnetic axis and the planet's rotation axis is the second largest in the Solar System after the one of Uranus, with an angle of ∼

47°. Additionally, there is a significant offset of ~ 0.5 Neptune radii between the dipole and the center of the planet, as well as appreciable non-dipolar components which are not yet well-determined (Holme and Bloxham, 1996; Ness et al., 1989). The origin of the magnetic field is unclear and weakly-constrained by past observations but it is believed that Neptune's large-scale magnetic field is due to a turbulent mean-field dynamo (Ruzmaikin and Starchenko, 1991). Fluxes of trapped high-energy (≥ 1 MeV) protons and electrons composing Neptune's radiation belts were measured in-situ (Stone et al., 1989). The radiation belts have a complex, dynamic structure and particle loss processes due to significant changes in the diurnally-varying magnetosphere configuration, which result from the large dipole tilt (Ness et al., 1989). Neptune's magnetosphere changes each planetary rotation between a configuration similar to other magnetized planets with a planar plasma disk in the equatorial plane to a unique configuration with a cylindrical plasma sheet, as it is illustrated in Fig. 1.

Link to exoplanets Increasing data on exoplanetary systems show that the properties of planets in our Solar System are not exceptionally unique compared to those in extrasolar ones (Martin and Livio, 2015). The observation of these systems in different stages of development provides information about the phases our own system has gone through. Therefore, investigating the evolution of our Solar System through the formation and evolution of extrasolar planetary systems is crucial and a current active field of research. Notably, a large fraction of (tens of percents) detected exoplanets are classified as Neptune- and mini-Neptune-like planets from their hydrogen- and helium-dominated atmospheres and similar sizes (Atreya et al., 2020; Zhu and Dong, 2021; Osborn et al., 2017; Martin and Livio, 2015; Cao et al., 2024). Neptune is likely more representative of similar-sized exoplanets than Uranus, which has been significantly altered by collisions, and may share a similar evolutionary history with them.

1.1.2 Triton

The Neptunian system offers a glimpse into the Solar System formation. While most of the Solar System has evolved from protosolar disk material into planets and moons, some material remains largely unaltered since its formation. This material is found in the Kuiper Belt, a region beyond Neptune filled with asteroids and small bodies. Because this material has undergone minimal change from Solar radiation, it provides a window into the Solar System early stages. Triton's retrograde orbit and the apparent lack of large moons orbiting Neptune suggest Triton was originally a member of a binary, similar to Pluton-Charon, orbiting the Sun in the Kuiper belt before being captured by Neptune (Agnor and Hamilton, 2006). Additionally, observations from Voyager 2 suggest that Triton has been, and may still be, geologically active. Significant tidal heating from Triton's capture and subsequent orbital circularization (Ross and Schubert, 1990), combined with obliquity tidal and radiogenic heating, may prevent the primordial ocean from freezing and provide heat for recent geological activities (Chen, Nimmo, and Glatzmaier, 2014).

1.2 Previous & Upcoming missions and proposals

The Voyager 2 probe is the only space probe that has visited the Neptunian system, completing a flyby on August 25, 1989. It revealed the differences and similarities of the Neptunian system compared to other giant planets in the Solar System. Having a more detailed comparison will provide common ground to studying the evolution of giant planets and their moons. Several mission concepts are being considered like the Neptune Odyssey NASA mission concept (Rymer et al., 2021), a Flagship-class orbiter and atmospheric probe to the Neptune–Triton system. The latter would focus on the study of the Neptunian system, from the planet, to its rings, magnetosphere and moons system. Proposed in 2019 to NASA's Discovery Program was the Trident mission proposal to Neptune's largest moon Triton (Sharma et al., 2022). The mission relies on a unique fast flyby of Triton to analyze its active geology and potential subsurface ocean.

2 Science case

2.1 Science objectives

The scientific theme of the NOSTROMO mission is to:

"Study Neptune and its moon Triton to better understand planetary systems formation and their habitability".

2.1.1 Origin and evolution of Neptune

The first scientific objective (**SO-1**) emphasizes on studying Neptune as a close-by "exoplanet" to better understand the formation of our own Solar System.

The most crucial measurement for understanding Neptune's formation is the bulk abundance of noble gases and their isotopic ratios, along with the isotopic ratios of hydrogen, oxygen, carbon, nitrogen and titanium (Rüfenacht et al., 2023). Another crucial way to constrain the formation processes of ice giants is to study their internal structure. We achieve this by inferring the gravity field from accurate trajectory measurements of the spacecraft.

The mission aims not only at understanding Neptune itself but also its unique and complex magnetospheric structures, which may be better representatives of planetary magnetospheres in the universe than previously thought. Therefore, NOSTROMO will measure the magnetic field to understand Neptune's dynamo and further constrain its interior structure. Additionally, accurate mapping of Neptune's magnetic field is essential for magnetic induction sounding techniques used to search for a potential subsurface ocean on Triton. For that, we need a complete coverage of Neptune's magnetic environment.

Detailed mapping of the magnetosphere helps identify spatial variations and temporal changes in the magnetic field, which are essential for understanding the underlying dynamo processes in Neptune's interior. Additionally, understanding the behavior of charged particles in Neptune's magnetosphere, including their sources, sinks, and transport mechanisms, can support inferring the characteristics of the magnetic field and its generation. Finally, understanding how Neptune's magnetosphere shields the planet not only from the solar wind but

Science objectives	Science sub-objectives
SO-1: Investigate the origin and evolution processes of Neptune as a proxy for exoplanets to advance planetary system evolution theories	SO-1.1: Characterize the interior structure of ice giants
	SO-1.2: Determine atmospheric composition of ice giants
	SO-1.3: Characterize the magnetospheric environment
SO-2: Understand the formation and evolution of Triton as a key to understanding the formation of our Solar system	SO-2.1: Determine the surface properties of Triton
	SO-2.2: Characterization of the atmosphere of Triton
	SO-2.3: Understand the interaction between Triton and Neptune
SO-3: Is Triton an habitable environment and how does it compare with other possible habitable environments	SO-3.1: Determine the internal structure of Triton
	SO-3.2: Determine the mechanism behind the plume activity

Table 1: Scientific objectives.

also from galactic cosmic rays can provide key insights into the habitability of exoplanets Cao et al., 2024.

2.1.2 Origin and evolution of Triton

The second science objective (**SO-2**) focuses on the origin and evolution of Neptune's largest moon, Triton. The Neptunian system offers a unique glimpse into the early Solar System. While most of the Solar System has evolved from protosolar disk material into planets and moons, some material remains largely unaltered since the formation of the Solar System. This material is found in the Kuiper Belt, a region beyond Neptune filled with asteroids and small bodies. Since this material has undergone minimal change, it provides insight into the Solar System's early stages. Fortunately, we don't need to travel to the Kuiper Belt to study it because Triton is likely a captured Kuiper Belt object (Agnor and Hamilton, 2006). Neptune's capture of Triton likely occurred through a binary-planet gravitational encounter.

Triton has an induced magnetosphere, primary controlled by electron-impact ionization from Neptune's magnetospheric electrons and solar photoionization (Benne, Benmahi, et al., 2024). In comparison to Titan, Triton has a denser ionosphere (Benne, Dobrijevic, et al., 2022), even though it is 4 times further away from its host planet than Titan. The magnetic environment of Triton is highly dynamic as a result of the complex, very dynamic magnetic field of Neptune (Masters et al., 2014). Molecular nitrogen escapes from sputtering of Triton's atmosphere resulting in loss rates of 10^{21} s^{-1}, with transient increases along Triton's obit (Lammer, 1995). The magnetospheric environment of Triton is complex, dynamic and little constraint by previous observations. A deeper investigation would improve our understanding of the atmospheric loss processes at Triton and the magnetopsheric sources responsible for both Triton and Neptune.

2.1.3 Habitability of Triton

Finally, the third scientific objective (**SO-3**) relates to the hypothetical habitability of Triton sub-surface ocean. This last objective aims to determine the habitability of Triton's environment, and compare it to other moons in the Solar System of astrobiological interest.

Active geyser-like eruptions were found at the surface of Triton, releasing clouds of dark materials rising up to 8 km in altitude and drifting downwind over 100 kilometers (Soderblom et al., 1990). These deposits of dark material are visible as black streaks on the surface of Triton and are suspected to be composed of complex organic compounds (Council, 2007).

3 Payload

This section presents the final payload suite and gives a short description of each instrument. The camera systems, UV-VIS-IR- and mass spectrometers and laser altimeter are all situated on the nadir (planet facing) plane of the spacecraft, while the magnetometer boom is pointing in the zenith direction. The energetic particle environment package sensors are distributed over the two horizon pointing planes and the nadir plane to increase its field of view.

3.1 Optical camera system (OCS)

The Narrow Angle Camera (NAC) will be used to study Triton's surface, providing high-resolution images. Its primary focus will be imaging Triton's plume region to investigate the distribution and direction of the plume deposits, offering information about wind direction. The Wide Angle Camera (WAC) will provide imaging to study Neptune's atmosphere, including cloud structures, the dark spots, lightning, and aurorae. Furthermore, the OCS, will allow for the possible detection and imaging of other Neptunian moons. Additionally, a filter wheel allows multi-spectral imaging. Overall, the camera will operate on the day-side for general mapping of the celestial bodies and on the night-side to capture lightnings.

Spectral range	(350–1050) nm
Pixel size	7.1 µm
Detector format	2048 x 2048 pixels^2
Focal length	15 mm (W) and 1500 mm (N)

Table 3: Instrument requirements for the OCS.

3.2 UV spectrometer (UVS)

The UltraViolet Spectrometer (UVS) is a photon-counting imaging spectrometer which offers multiple applications. These range from stellar/solar occultation of Neptune's and Triton's atmospheres useful for studying their composition and dynamics, to nadir observations of aurora and lightning, as well as Triton's surface albedo. UVS will also help us detect and understand active plumes. Trajectory and instrument requirements are chosen such that the spatial resolution during the closest approach will be approximately 140 m. There are multiple heritage instruments flying for example on JUNO and JUICE. UVS will need redesigned apertures and optics to operate at least in star occultation, a push-broom and a feature mirror-pointing mode (Gladstone et al., 2017).

Science objectives	Optical camera (OCS)	UV spectrometer (UVS)	VIS-IR spectrometer (VIS)	Laser altimeter (LA)	Magnetometer (Mag)	EPEP	Mass spectrometer (MS)	Radio science (RSE)
SO 1-1 ♆					●			●
SO 1-2 ♆	●	●	●		○	●	●	○
SO 1-3 ♆	○	○	○		●	●		
SO 2-1 ☽	●	●	●	●				
SO 2-2 ☽	○	●	●			○	●	○
SO 2-3 ♆/☽					●	●		○
SO 3-1 ☽					●			●
SO 3-2 ☽	●	○	●	●			○	

Table 2: Overview of addressed scientific objectives (Neptune ♆and Triton ☽) by each instrument. Primary instruments are marked by ●, supporting instruments by ○.

Spectral range	(68 to 210) nm
Spectral resolution	$\leq$ 0.6 nm
Pixel scale	(350 ± 5) µrad/pixel
Slit FOV	2°
Scanning mirror range	(−30 to 30)°

Table 4: Instrument requirements for the UVS.

3.3 VIS-IR spectrometer (VIS)

The hyper-spectral imaging spectrometer VIS will primarily provide spectral information for the chemical identification of Neptune's atmosphere and Triton's surface. The instrument helps to study lightning, IR-aurorae, cloud features and the ring structure of Neptune. Also, it will help to better understand the ice layer and surface features, as well as the plumes and their dark deposits on the surface of Triton. The instrument will either operate in a push-broom mode, scanning the surface and atmosphere to build a global mosaic, or in stellar occultation mode, scanning the atmosphere vertically, or with mirror-pointing, allowing a localized spectral analysis of small features. The spatial resolution on Triton's surface will be 72 m. The VIS will take advantage of the heritage created by MAJIS flying on JUICE (Poulet et al., 2024). The required low temperature of 90 K for the detector head is the one driving the thermal design.

Spectral range	(0.5 to 5.55) µm
Spectral resolution	$\leq$ 0.6 nm (VIS-NIR) $\leq$ 5 nm (IR)
Pixel scale	(180 ± 5) µrad/pixel
Number of pixels	400
Slit FOV	2°

Table 5: Instrument requirements for the VIS.

3.4 Laser altimeter (LA)

The laser altimeter to be used in the mission is equipped with a Nd:YAG laser, operating at a wavelength of 1064 nm and a pulse length of 5 ns. The laser has a pulse repetition rate of 10 Hz, which results in a maximum sampling distance of 105 meters at periapsis when observing the south pole region (Thomas et al., 2021). The primary objective of this instrument is to obtain topographical data for mapping Triton's surface and to measure possible periodic tidal deformations. These measurements will help assess the potential detachment of the icy shell from the solid interior, possibly indicating a subsurface ocean. Finally, by determining Triton's amplitude of libration, we can constrain the thickness of the ice layer (Hussmann et al., 2019).

3.5 Magnetometer (Mag)

A dual sensor fluxgate configuration combined with a scalar sensor will be employed to assess the magnetic fields around Neptune and Triton. These measurements aim to explain Neptune's internal composition and enhance our comprehension of its distinctive magnetic field. By observing the inducing and induced magnetic fields at low altitudes while orbiting Triton, we aspire to discern the moon's interior conductivity structure, potentially revealing subsurface ice layers (Saur, Neubauer, and Glassmeier, 2010). The gathered data will undergo a Principal Component Analysis to investigate oceanic properties (Cochrane et al., 2022).

Measurement range	(−50 000 to 50 000) nT
Measurement accuracy	better than 0.1 nT
Measurement frequency	$\leq$ 1 Hz
Time resolution	(1 to 5) s

Table 6: Instrument requirements for the Mag.

3.6 Energetic particle environment package (EPEP)

The in-situ particle environment package, a modified PEP-inspired instrument suite, includes ion and electron sensors, an Energetic Neutral Atom (ENA) camera, and a Digital Processing Unit (DPU). It provides comprehensive measurements of plasma composition and 3D particle distributions with detailed time resolution. The ion sensor detects positively and negatively charged ions with a hemispherical field of view (FoV), while the electron sensor covers a similar energy range with the same FoV. The ENA camera captures high-resolution images of energetic neutral atoms, offering a global view of Neptune's magnetosphere. The electron and proton sensors are placed strategically on opposite decks of the spacecraft, for full angular coverage and they can operate in two different modes: in Mode 1 the suite measures electrons with the electron sensor and ions with the ion sensor with a high energy resolution using 12 energy channels, while in Mode 2 it measures electrons with the ion sensor and ions with the electron sensor with a low energy resolution using 5 energy channels for the same energy range. The DPU manages data processing with high computational power and redundancy to ensure continuous operation and data integrity. (JSWT, 2014)

Detected particles	electron, ions and Energetic Neutral Atoms (ENAs)
e^- energy range	1 eV to 50 keV
Ion energy range	1 eV to 41 keV
ENA energy range	(0.5 to 300) keV
Time resolution	4 s

Table 7: Instrument requirements for the EPEP.

3.7 Mass spectrometer (MS)

A time-of-flight neutral-ion mass spectrometer is used to perform in-situ measurements in Neptune's atmosphere and Triton's upper atmosphere and ionosphere (Justh and Hoffman, n.d.; Lellouch et al., 1992; Benne, Dobrijevic, et al., 2022). Hereby, the instrument will measure the absolute abundance of charged and uncharged elementary particles, molecules and organic compounds, as well as the absolute pressure. Along the S/C trajectory the NMS will a achieve a spatial resolution of at least 50 km. The produced vertical profiles will range from (1000 to 4000) km above the 1 bar level in the case of Neptune and from(200 to 1000) km above the surface in the case of Triton. One provider for such an instrument is the University of Bern with the heritage instrument NIM on board JUICE, which is optimised for deep space missions in terms of mass, power consumption and telemetry rate, and meets most of the requirements. However, further development will be needed to reach the required operating pressure range [1].

Detected species	Neutrals & ions: elementary particles, molecules and organic compounds.
Mass range	(1 to 300) amu
Mass resolution $\frac{M}{\Delta M}$	> 500
Spectra output	every ≤ 2 s (Neptune), every ≤ 25 s (Triton)
Pressure range	$\leq 5 \times 10^{-5}$ mbar
Pressure gauge range	$(1 \times 10^{-11}$ to $1 \times 10^{-1})$ mbar

Table 8: Instrument requirements for the Mass spectrometer.

3.8 Radio Science Experiment (RSE)

The Radio Science instrument tracks Doppler shift in radio signals sent between spacecraft and Earth. It aims to constrain the internal structure and gravity field of Neptune and Triton with an accuracy of $\Delta v = 10\,\mu$m/s, which includes the localization of the subsurface ocean at Triton, if it is present. Additionally, the instrument will be able to provide an atmospheric occultation profile and information such as the temperature and pressure of the Neptunian system.

4 Mission design

4.1 Cost breakdown

The preliminary cost breakdown for the NOSTROMO mission was conducted in consultation with the Head of Science Missions Studies from ESA, Peter Falkner and sums up to about 1.36 B€ for the full mission envelope including inflation. Special expenses for utilizing RTGs have been added to the industrial costs covering production of the spacecraft (S/C) as well as to the launcher costs to facilitate the export restrictions of the technology. Due to the extensive mission timeline the mission and science operations costs have been adjusted accordingly.

4.2 System Drivers

Certain system drivers had a strong influence on mass, power, communication and data budget of NOSTROMO. These included the use of Multi-Mission Radioisotope Thermoelectric Generators (MMRTGs), which, as will be discussed in Section 5.4, deliver only a limited amount of power during the active mission lifetime due to degradation. Further system drivers were the payload suite, as well as the data downlink, where the payload suite has to fulfil the science case, as described in Section 3, and the data downlink has to send the science data back to Earth with a low downlink data rate, as will be discussed in Section 5.1. These both, when in operation, draw an amount of power that cannot be provided by the MMRTGs alone.

Item	Estimation in Mio. €	Note
Industrial Cost	650,00	spacecraft including RTGs
Project Team	162,50	
MOC & SOC	130,00	due to long mission duration
Contigency & Margin	141,38	
Launcher Cost	150,00	including nuclear restrictions
Total mission cost	1233,88	
Adjusted for 10% inflation	**1357,26**	

Table 9: Cost breakdown.

These therefore required additional batteries to be included aboard NOSTROMO, where in turn their recharge time acted as another system driver. This will further be discussed in Section . This resulted in the on-orbit times around Neptune and Triton being subdivided into sections, where each section was allocated a specific function, as can be seen, in the case of Neptune, in the graph in Figure 2. A similar distribution was defined for the Triton orbit. In the following, the singular subsystems that interact as described above will be discussed in more detail.

[1]Also, further studies of Trtiton's and Neptunes atmospheric pressure profiles are needed.

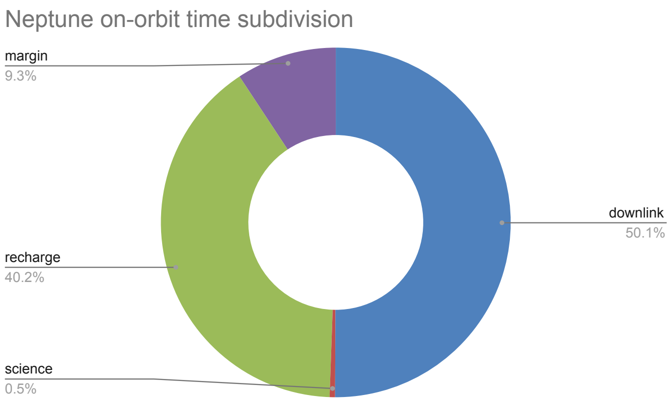

Figure 2: Illustration of Neptune on-orbit time subdivision.

4.3 Mission phases and Orbits

4.3.1 Earth-Neptune transfer

The interplanetary transfer can be split in two main legs: the journey from Earth to Jupiter, and that from Jupiter to Neptune. In order for a spacecraft to reach Jupiter, at least 9 km/s of hyperbolic excess velocity is needed. Such velocity can be reached in a fuel-efficient way only by using gravity assists with the terrestrial planets. Based on the heritage of past and current missions, there are three main sequences of flybys that can be used to reach Jupiter: Earth-Venus-Earth-Earth (e.g. Galileo), Earth-Mars-Earth (e.g. Europa Clipper) and Earth-DSM-Earth, where a deep space maneuver (DSM) is executed between the launch and the first gravity assist.

Launch	Flyby sequence	Time of flight [years]	Launch v_∞ [km/s]	Δv [km/s]
25/12/2048	EVEEJ	18.7	3.14	2.21
25/12/2048	EVEEJ	20.9	3.17	1.81
11/11/2048	EMEJ	20.7	5.19	3.28
10/2/2054	E(DSM)EJ	15.8	5.23	2.32

Table 10: Optimal trajectories using different fly-bys.

The launch window is primarily driven by Jupiter and Neptune, as the correct phasing (alignment) between the two planets determines the entire feasibility of the transfer. From a porkchop analysis, it is possible to infer that the spacecraft should reach Jupiter between 2054 and 2058 in order to exploit the gas giant's gravity in an optimal way. Since the journey from Earth to Jupiter via flybys can take between 4 and 7 years, this places the range for possible departure dates between 2048 and 2054. Following this preliminary analysis, the overall trajectory optimization problem from Earth to Neptune has been modeled using a multi-arc Lambert propagator. The optimization variables of the design space include the departure time (constrained to the previously mentioned range), the time at each swingby node, the launch C3 and the deep space maneuver magnitude and location (if present). The design space is also constrained by the C3 performance of the selected launcher, the minimum periapsis distance for gravity assist (necessary for thermal and radiation considerations) as well as the arrival declination angle at Neptune (this needs to be low with respect to Neptune's equator, to allow targeting the orbital plane of Triton). The problem was solved via global heuristic search, using the Differential Evolution algorithm that is available on PyGMO.

The most significant results of the optimization are reported in Table 4.3.1. It can be noticed that Mars does not offer competitive solutions since it is never properly aligned with the Earth and Jupiter during the investigated time frame. Using a transfer via Venus was found to be very fuel-efficient, with a minimum ΔV of 1.8 km/s for a total of 21 years of flight, whereas the optimal solution using the DSM drastically reduces to 15.8 years the journey to Neptune, although at an increased cost of 2.3 km/s. The advantage of this latter option in terms of flight time has been deemed sufficient to justify the increased propellant cost, therefore this trajectory has been selected. Given that it requires a v_∞ at launch of 5.2 km/s, and considering the preliminary mass budget, the Ariane 64 in its EVO configuration has been identified as the candidate launch vehicle, with a capacity up to 7.4 tons.

Finally, a sensitivity analysis has been carried out in order to identify suitable backup launch windows. The optimal launch window starts on 10th February 2054 and lasts for 30 days. A second opening of 14 days is available approximately three months later starting from the 4th of May; a more conservative backup launch window opening on the 1st of April 2055 has also been considered should there be major issues with the manufacturing and delivery of the spacecraft. For these three launch dates, a Pareto front analysis has been carried out in order to support the iterative design cycle, and allow to trade off propellant mass with additional flight time. In particular, the worst-case scenario, which corresponds to the launch window in 2055, has been used to size the propulsion system, with 3 km/s of ΔV required for a total flight time of 18 years.

4.3.2 Injection and final orbit around Neptune

The spacecraft is designed to reach Neptune on a highly eccentric injection orbit (0.98). The low injection periapsis is intended to minimize the ΔV while maximizing close encounters with Neptune. Subsequently, the apoapsis will be reduced through a series of flybys around Triton using resonant orbits to achieve Neptune's science orbit. This orbit is selected to increase the number of flybys around Triton and shorten the period, allowing for more frequent scientific observations. The transition from Neptune's injection orbit to its science orbit will be done with a moon tour, taking approximately three months with a ΔV of 100 m/s.

4.3.3 Injection and final orbit around Triton

After a four-year mission around Neptune, the next phase aims to enter the science orbit around Triton. **article** proposed a low-energy endgame using Tisserand Leveraging Maneuver (TILT) to achieve a cheap insertion to Triton in approximately three months with a delta-v of 378 m/s. This cost includes maneuvers to target resonant orbits and raise the periapsis from the Neptune science orbit, with successive flybys around Triton and the final injection into Triton's science orbit. Two science orbits around Triton were designed to guarantee 68 and 325 days at altitudes of less than 300 km

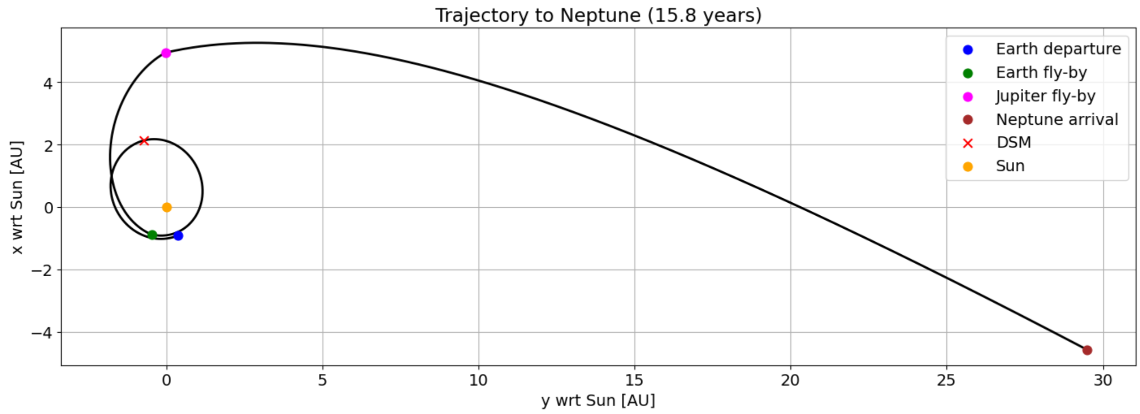

Figure 3: Interplanetary transfer final trajectory.

and 900 km, respectively, enabling high-precision measurements from the mass spectrometer and the laser altimeter. The first eight months will be spent in a highly inclined orbit (polar) with an inclination of 87° to ensure full coverage of Triton. This orbit is unstable due to perturbations from Neptune, necessitating a monthly 10 m/s maneuver to maintain the required inclination and altitude. The last four months will be in a second orbit with an inclination of 35°, chosen for its high stability and not requiring station-keeping, thus allowing for a potential mission extension. An NRHO orbit around Triton was also considered due to its high inclination and stability, but its synchronization with Triton's rotation was deemed problematic.

4.3.4 Mission end-of-life and Decommissioning

Considerations were made for the end-of-life phase of the mission, with two options under review: a controlled reentry onto Triton or a crash onto Neptune. According to ESA's Planetary Protection Article IX of the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space,, Triton is categorized as a Category II* object, allowing for both options. However, a controlled reentry onto Triton would necessitate an examination of potential contaminations to respect Category II*'s requirement, particularly with the RTGs, which, depending on the final impact, might melt the ice and reach the subsurface ocean. The first option was dismissed due to the high cost of leaving Triton's gravitational influence at 305 m/s and the velocity of 4 km/s needed to crash into Neptune. Therefore, the selected mission's decommissioning is a controlled reentry onto Triton. As the mission ends, the battery will be fully charged, and the communication antenna will be pointed towards Earth to allow the collection of measurements from the mass spectrometer and the magnetometer during the 30 to 60 minutes of reentry.

5 Spacecraft design

5.1 Communications

The NOSTROMO spacecraft (S/C) will use a communication system with two antennas: a High-Gain Antenna (HGA) with a 3-meter diameter and a Medium-Gain Antenna (MGA) with a 0.5-meter diameter dish. The HGA, which has an antenna gain of 57.4 dB, allows for a downlink of 985 Mbit/day and supports a maximum uplink rate of 1.9 Mbit/s. This antenna serves as the primary data link for scientific transmission. The MGA, with an antenna gain of 41.9 dB, achieves a downlink data rate of 104 Mbit/day and an uplink rate of 58.9 kbit/s, handling telemetry and housekeeping communications.

The ESA Deep Space Antennas network will be used as the ground segments for the mission. The ground segment includes 35-meter deep space terminals (CEB1 in Spain and MLG1 in Argentina) and the upgraded New Norcia station (NNO1) in Australia. For redundancy, NASA's 70-meter terminals in California, Madrid, and Canberra are available. Operations occur in the Ka-Band, with a 32.0 GHz downlink and 34.5 GHz uplink.

In the Neptune orbit, the system allows up to 23 hours of contact per day, and in Triton orbit, up to 20 hours per day, facilitated by the distributed ground stations.

5.2 Structure

The S/C main body has a rectangular shape with the dimensions of $3 \times 3 \times 7\,\mathrm{m}^3$. The S/C will maintain active attitude control so that the side (nadir plane) with the optical and spectral instruments faces the target. The placement of the scientific instruments, the thermal system components and the power system components is highlighted in Figure 4.

The high radiation flux during the flyby at Jupiter is a recognized problem. The top-level strategy to mitigate this issue is to centralize and shield S/C and payload electronics in a vault. The payload electronics are not in operation during the flyby, so the sensors only need to be protected from degradation/destruction, not from improved SNR.

This design ensures that the S/C can be accommodated by the Ariane 6 payload fairing. Additionally, at the base of the engine, there are attachment points for the payload adapter.

5.3 Mass Budget

As shown in Table 11, the preliminary mass budget was first estimated top-down by averaging subsystem mass data from the comparable mission concepts Neptune Odyssey and Triton World Surveyor, presented in the 2023-32 NASA Decadal Survey for Planetary Science and Astrobiology (*Origins, Worlds, and Life* 2023). Subsequently, specific items were selected for certain subsystems to populate the mass budget bottom-up. For each subsystem, design maturity mass margins according to the ESA margin philosophy for science assessment studies were then applied (ESTEC, 2012). Margin values of 10% and 20%, for off-the-shelf and newly designed or majorly modified items, respectively, were applied on a case-by-case basis. For example, the flight-qualified propulsion

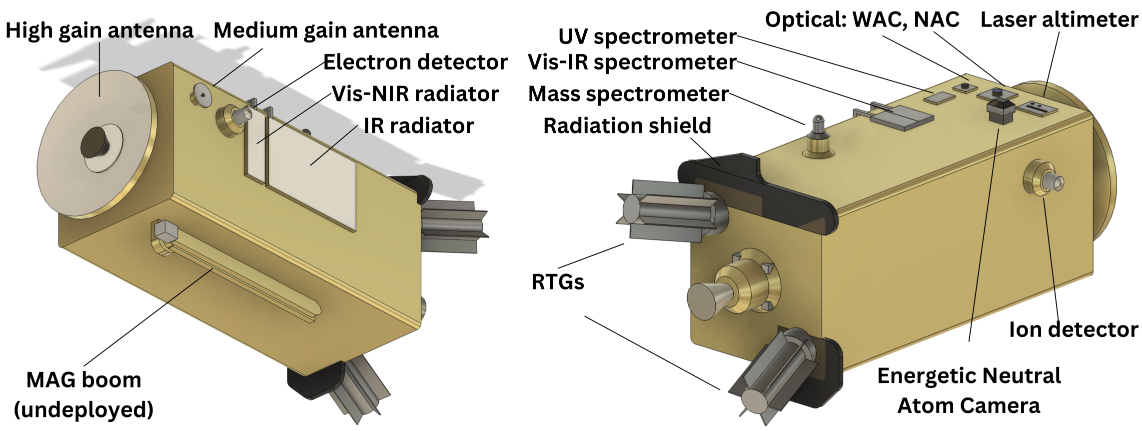

Figure 4: Spacecraft model in the launch configuration with description of the components.

system, which was planned for the Neptune Odyssey concept, was rated with a margin of 10%. The structures & mechanical system, which will need to be newly developed, was rated with a margin of 20%, as well as the payload. The total dry mass, consisting of the bus and payload mass, was rated with a system-level margin of 20%, still according to the same margin philosophy. Taking the Δv from trajectory analysis into account, as well as margins on both Δv and propellant mass, as shown in Table 12, the wet mass of 7 tons was calculated, as shown in Table 13. This wet mass was compared with the launcher mass capability of 7.4 tons, yielding a 5% mass margin.

Inputs	Values
Isp	326 s
Delta V without margin	3806 m/s
Propellant margin	25.00 %
Dry mass	1820 kg
Propellant	**5205 kg**
Total	7024 kg

Table 13: Propellant mass budget.

Subsystem	best estimate [kg]	contigency [%]	max. expected value [kg]	bus dry mass contribution [%]
command and data handling	46	10	51	3.7
GNC	64	10	70	5.2
power	261	10	287	21.0
harness	77	20	92	6.8
thermal	75	20	90	6.6
communications	120	20	144	10.5
propulsion	197	10	217	15.9
structures and mechanical	305	20	365	26.7
payload adapter			50	3.7
total bus	**104**	**20**	**150**	**100.0**
payload				
total dry	**1248**		**1516**	
total dry with system margin		20%	1820	
propellant			5205	
total wet			**7024**	
max. possible value, total dry			7400	
margin kg			**376**	
margin %			5	

Table 11: Summary of the mass budget.

Phase	Delta V	Margin	Delta V
Transfer Earth-Neptune	3000 m/s	5%	3150 m/s
Insertion into Triton orbit	472 m/s	5%	496 m/s
Stationkeeping	80 m/s	100%	160 m/s
Sum			**3806 m/s**

Table 12: Mission profile ΔV budget.

5.4 Electrical Power System

The main power source for the NOSTROMO mission consists of four MMRTGs, each using plutonium-238. Each MMRTG generates 110 watts of electrical power, resulting in a total power output of 440 watts for the spacecraft. Moreover, each MMRTG releases 2000 watts of thermal energy. As a result of the 88-year half-life of plutonium-238, the power output of each MMRTG will degrade to about 90.3 watts over the planned 25-year mission, providing a total power output of 361.4 watts at the end of the mission.

To complement the MMRTGs, especially during periods of high power demand, and to offset the degradation of MMRTG power, the spacecraft is equipped with rechargeable batteries. The chosen battery type is the SAFT VL51 ES, with an energy capacity of 186 Wh and a specific energy of 175 Wh/kg (al., 2018).

The maximum power requirement, primarily during data link operations in Neptune orbit, is 270 W for 29.4 h, which translates to an energy requirement of 7961 Wh. To meet this requirement, 43 batteries are needed, providing a total energy capacity of 13113 Wh after accounting for a 6% energy degradation over 25 years.

As batteries are generally arranged in fixed stacks, several stacks were chosen, totaling 75 batteries. This arrangement not only meets the energy requirements but also serves to lower the Depth of Discharge (DoD) and decrease recharge times. With this setup, the batteries are discharged to 61% DoD during each orbit and take approximately 23.61 hours to recharge from this state.

Subsystems Modes	Science	Science 2	Manoeuvre	Data-Link	Safe	Cruise	Battery
Payload	170	0	0	0	0	0	0
CDH	38	38	35	35	36	27	2
GNC	81	81	49	66	46	46	33
Power	45	45	45	45	45	45	45
Thermal	20	20	80	20	0	0	0
COMS	0	120	0	300	120	120	15
Propulsion	21	21	130	21	26	26	26
Total	375	325	338	486	273	264	121
Margin	30%	30%	30%	30%	30%	30%	30%
Total incl. Margin	487	422	439	632	355	343	157
RTG output	361	361	361	361	361	361	361
Excess	-126	-61	-78	-270	6	18	205
Power draw on battery	126	61	78	270	0	0	0

Table 14: Power budget, all values in W except where marked.

5.5 Propulsion

The primary propulsion for the NOSTROMO mission will be provided by the Aerojet Rocketdyne HiPAT Dual-Mode 445N engine. The same engine was planned for use in the Neptune Odyssey concept.

The engine uses hydrazine (N_2H_4) and dinitrogen tetroxide (NTO), providing a thrust of 445 N. This is sufficient for the major maneuvers required during the mission. With a specific impulse of 326 seconds, the HiPAT engine ensures high efficiency for the duration of the mission.

5.6 Attitude Control & Determination System

5.6.1 Components and Configuration

The Attitude Determination and Control System (ADCS) for NOSTROMO follows the component selection and configuration of the Neptune Odyssey concept, incorporating both actuators and sensors to achieve reliable and precise attitude control.

The ADCS controls the spacecraft's attitude using reaction wheels and thrusters. Four reaction wheels (one redundant) allow fine adjustments by changing their rotational speed, leveraging angular momentum conservation. A set of sixteen 4.4 N monopopellant (N_2H_4) thrusters provides coarse adjustments, desaturates the reaction wheels, and supports safe mode operations by expelling propellant to generate torque. The ADCS uses various sensors to determine attitude: two star trackers (one redundant) capture star images and compare them with a star catalog for precise orientation, sun sensors detect the Sun's position for coarse information, and an Inertial Measurement Unit (IMU) measures acceleration and rotational rates using accelerometers and gyroscopes.

5.6.2 ADCS Modes and Operations

The ADCS operates in different modes depending on the mission phase and operational requirements. Each mode utilizes specific sensors and actuators to achieve the desired attitude control.

ADCS Mode	Modes	Sensors	Actuators
Fine Acquisition	Cruise, Science 1, Science 2, Data Link	Star Trackers, Sun Sensors, IMU	Reaction Wheels
Rough Acquisition	Battery Charge	Sun Sensors, IMU	Reaction Wheels
Slew	Manoeuvre	Star Trackers, Sun Sensors, IMU	Reaction Wheels, Thrusters
Safe	Platform/Safe	Sun Sensors, IMU	Thrusters

Table 15: ADCS modes.

5.6.3 Performance Requirements

The ADCS is designed to meet performance requirements to ensure the mission's success. The primary driver for the ADCS performance is the need to achieve precise pointing accuracy during scientific observations, particularly in worst-case scenarios such as at periapsis around Neptune and Triton. The slow rates in science mode are given as follows: 0.02°/s around Neptune and 0.006°/s around Triton. These slew rates are vital for maintaining stable and accurate pointing of scientific instruments, enabling efficient data collection during close encounters with Neptune and Triton.

5.7 Thermal System

The NOSTROMO mission will traverse varied thermal environments from Earth's high solar irradiance to the cold expanse of interplanetary space and the Neptunian system. To maintain operational temperatures for the spacecraft systems and instruments, the thermal control system (TCS) for the NOSTROMO mission includes a combination of passive and active thermal management solutions.

Passive Thermal Control:

- **Multi-Layer Insulation (MLI):** Reduces heat loss in the cold outer solar system. Mitigates the absorption of electromagnetic radiation in the initial mission phase.
- **Thermal isolation:** Thermally decouples sensitive instruments from the S/C body.
- **Heat Pipes and Radiators:** Transfers and dissipates excess heat from the instruments.

Active Thermal Control:

- **Electric Heaters:** Maintain stable sensor temperatures during operation.

The thermal design of the NOSTROMO mission ensures that the spacecraft maintains operational temperatures using 8 layers of MLI covering the S/C surface area, effectively regulating temperatures without the need for radiators, achieving 29 °C at Earth and 22 °C at Neptune distances.

The Vis-IR spectrometer, requiring precise cooling, utilizes two dedicated radiators to achieve 90 K for the IR sensor and 130 K for the VIS sensor, with sizes of 3.7 m^2 and 0.75 m^2 respectively. Each sensor head also has a dedicated electric heater to manage temperature fluctuations if the radiator is shadowed.

5.8 Data Budget and On-board Computing

In order to facilitate all the memory needs of the missions science experiments, reference mission concepts, among them the Uranus Orbiter and Probe from (*Origins, Worlds, and Life* 2023) were analyzed. Primary contributor to the data budget was the camera producing data at around 40 Mbit/s. Considering the remaining science experiments maximum data rates, total operation time, and the orbital durations at Neptune and Triton the OBC was then calculated to require 1024 GB of storage. This memory size allows for 5 days of continuous data collection around Neptune and 43 days around Triton.

6 Descoping options

The instrument identified to most likely be descoped is the laser altimeter. It was first selected by its priority and secondly because it is going to be only utilized in orbit around Triton. Thirdly it was selected since the data for its science question can be partially constrained by utilizing the camera for topological imaging and the magnetometer.

7 Conclusion

The NOSTROMO mission aims to substantially extend our knowledge about the Neptunian system, the formation process of the solar system and tries to establish a connection to the most common types of exoplanets. Investigating the interior of Tritons and its suspected subsurface oceans will increase our understanding of habitable areas outside of the currently established boundaries. By proposing the concept, addressing the scientific questions, the mission profile, the spacecraft design, and the application of the instruments, Team Red of 2024s Alpbach Summer School hopes to broaden our understanding of astrophysics, planetary science, astrobiology and exoplanet research.

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References

Agnor, Craig B. and Douglas P. Hamilton 2006. *Neptune's capture of its moon Triton in a binary–planet gravitational encounter. Nature.* DOI: 10.1038/nature04792

al., Borthomieu et 2018. *Saft VL51ES Space Cell Qualification Status. SAFT*

Atreya, Sushil K. et al. 2020. *Deep Atmosphere Composition, Structure, Origin, and Exploration, with Particular Focus on Critical in situ Science at the Icy Giants. Space Science Reviews.* DOI: 10.1007/s11214-020-0640-8

Benne, B., B. Benmahi, et al. 2024. *Impact of the transport of magnetospheric electrons on the composition of the Triton atmosphere. Astronomy & Astrophysics.* DOI: 10.1051/0004-6361/202346699

Benne, B., M. Dobrijevic, et al. 2022. *A photochemical model of Triton's atmosphere paired with an uncertainty propagation study. Astronomy & Astrophysics.* DOI: 10.1051/0004-6361/202244447

Berenguer, Ch and K Katsonis. *Modeling and diagnostics of H/He mixture high temperature plasmas*

Cao, Xin et al. 2024. *Science return of probing magnetospheric systems of ice giants. Frontiers in Astronomy and Space Sciences.* DOI: 10.3389/fspas.2024.1203705

Chen, E.M.A., F. Nimmo, and G.A. Glatzmaier 2014. *Tidal heating in icy satellite oceans. Icarus.* DOI: 10.1016/j.icarus.2013.10.024

Cochrane, C. J. et al. 2022. *Single- and Multi-Pass Magnetometric Subsurface Ocean Detection and Characterization in Icy Worlds Using Principal Component Analysis (PCA): Application to Triton. Earth and Space Science.* DOI: 10.1029/2021EA002034

Council, National Research 2007. *Exploring Organic Environments in the Solar System.* DOI: 10.17226/11860

1997. *Encyclopedia of Planetary Science.* DOI: 10.1007/1-4020-4520-4

ESTEC, ESA 2012. *Margin philosophy for science assessment studies. ESA UNCLASSIFIED*

Fulton, Benjamin J. and Erik A. Petigura 2018. *The California-Kepler Survey. VII. Precise Planet Radii Leveraging Gaia DR2 Reveal the Stellar Mass Dependence of the Planet Radius Gap. The Astronomical Journal.* DOI: 10.3847/1538-3881/aae828

Gladstone, G. Randall et al. 2017. *The Ultraviolet Spectrograph on NASA's Juno Mission. Space Science Reviews.* DOI: 10.1007/s11214-014-0040-z

Gomes, R. et al. 2005. *Origin of the cataclysmic Late Heavy Bombardment period of the terrestrial planets. Nature.* DOI: 10.1038/nature03676

Holme, Richard and Jeremy Bloxham 1996. *The magnetic fields of Uranus and Neptune: Methods and models. Journal of Geophysical Research: Planets.* DOI: 10.1029/95JE03437

Hubbard, W. B. et al. 1991. *Interior Structure of Neptune: Comparison with Uranus. Science.* DOI: 10.1126/science.253.5020.648

Hussmann, Hauke et al. 2019. *The Ganymede laser altimeter (GALA): key objectives, instrument design, and performance. CEAS Space Journal.* DOI: 10.1007/s12567-019-00282-8

Ingersoll, Andrew P. 1990. *Atmospheric Dynamics of the Outer Planets. Science.* DOI: 10.1126/science.248.4953.308

JSWT 2014. *Definition Study Report. ESA*

Justh, H L and J Hoffman. *Neptune Global Reference Atmospheric Model (Neptune-GRAM): User Guide*

Lammer, H. 1995. *Mass loss of N2 molecules from Triton by magnetospheric plasma interaction. Planetary and Space Science.* DOI: 10.1016/0032-0633(94)00214-C

Lellouch, E. et al. 1992. *A model of Triton's atmosphere and ionosphere. Advances in Space Research.* DOI: 10.1016/0273-1177(92)90427-Y

Martin, Rebecca G. and Mario Livio 2015. *The Solar System as an exoplanetary system. The Astrophysical Journal.* DOI: 10.1088/0004-637X/810/2/105

Masters, A. et al. 2014. *Neptune and Triton: Essential pieces of the Solar System puzzle. Planetary and Space Science.* DOI: 10.1016/j.pss.2014.05.008

Morbidelli, A. et al. 2012. *Explaining why the uranian satellites have equatorial prograde orbits despite the large planetary obliquity. Icarus.* DOI: 10.1016/j.icarus.2012.03.025

Ness, Norman F. et al. 1989. *Magnetic Fields at Neptune. Science.* DOI: 10.1126/science.246.4936.1473

2023. *Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032.* DOI: 10.17226/26522

Osborn, H. P. et al. 2017. *K2-110 b: a massive mini-Neptune exoplanet. Astronomy & Astrophysics.* DOI: 10.1051/0004-6361/201628932

Poulet, F. et al. 2024. *Moons and Jupiter Imaging Spectrometer (MAJIS) on Jupiter Icy Moons Explorer (JUICE). Space Science Reviews.* DOI: 10.1007/s11214-024-01057-2

Ross, Martin N. and Gerald Schubert 1990. *The coupled orbital and thermal evolution of Triton. Geophysical Research Letters.* DOI: 10.1029/GL017i010p01749

Rüfenacht, Miriam et al. 2023. *Genetic relationships of solar system bodies based on their nucleosynthetic Ti isotope compositions and sub-structures of the solar protoplanetary disk. Geochimica et Cosmochimica Acta.* DOI: 10.1016/j.gca.2023.06.005

Ruzmaikin, A. A. and S. V. Starchenko 1991. *On the origin of Uranus and Neptune magnetic fields. Icarus.* DOI: 10.1016/0019-1035(91)90165-P

Rymer, Abigail M. et al. 2021. *Neptune Odyssey: A Flagship Concept for the Exploration of the Neptune–Triton System. The Planetary Science Journal.* DOI: 10.3847/PSJ/abf654

Saur, Joachim, Fritz M. Neubauer, and Karl-Heinz Glassmeier 2010. *Induced Magnetic Fields in Solar System Bodies. Space Science Reviews.* DOI: 10.1007/s11214-009-9581-y

Sharma, Priyanka et al. 2022. *Mission Planning for Trident: Discovery proposal to Neptune's moon, Triton. 2022 IEEE Aerospace Conference (AERO).* DOI: 10.1109/AERO53065.2022.9843368

Smith, B. A., L. A. Soderblom, D. Banfield, et al. 1989. *Voyager 2 at Neptune: Imaging Science Results. Science.* DOI: 10.1126/science.246.4936.1422

Smith, B. A., L. A. Soderblom, R. Beebe, et al. 1986. *Voyager 2 in the Uranian System: Imaging Science Results. Science.* DOI: 10.1126/science.233.4759.43

Soderblom, L. A. et al. 1990. *Triton's Geyser-Like Plumes: Discovery and Basic Characterization. Science.* DOI: 10.1126/science.250.4979.410

Stone, E. C. et al. 1989. *Energetic Charged Particles in the Magnetosphere of Neptune. Science.* DOI: 10.1126/science.246.4936.1489

Thomas, N. et al. 2021. *The BepiColombo Laser Altimeter. Space Science Reviews.* DOI: 10.1007/s11214-021-00794-y

Zhu, Wei and Subo Dong 2021. *Exoplanet Statistics and Theoretical Implications.* DOI: 10.48550/ARXIV.2103.02127