Triton: Fascinating Moon, Likely Ocean World, Compelling Destination!

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Short Title: Triton, a Candidate Ocean World
Abstract

Triton is an important signpost in understanding the diverse populations of both Ocean Worlds and Kuiper Belt Objects. As a likely ocean world, it is unique by virtue of its kidnapped history from the Kuiper Belt: its large orbital inclination makes it the only ocean world thought to be primarily heated by obliquity tides (Nimmo and Spencer, 2015). It is volatile-rich due to its formation in the outer Solar System and its unusual surface geology may be the product of cryovolcanism. Observations from New Horizons and Cassini motivate re-examination of Triton datasets and models, with value for comparative planetology of ocean worlds and KBOs, most notably with Europa, Enceladus, Titan, and Pluto. We re-explore old datasets with the new perspective of the importance of ocean worlds in our Solar System and the search for life.

1. Introduction - Why Explore Triton?

Neptune’s moon Triton has been explored by just one spacecraft, Voyager 2, in 1989. Images revealed a unique geologically young surface with landforms not found anywhere else in the Solar System (Smith et al. 1989). Plumes erupt from a surface with a temperature of just 38K (Conrath et al. 1989). A tenuous nitrogen atmosphere is in vapor pressure equilibrium with its surface ices, similar to Pluto (Broadfoot et al. 1989; Tyler et al. 1989; Stern et al. 2018). Triton is also noteworthy for its retrograde, highly inclined orbit, making it almost certainly a captured Kuiper Belt dwarf planet, with a differentiated interior heated by tidal braking (McKinnon et al. 1995; Agnor and Hamilton 2006). Triton, nearly a twin in size to Pluto, provides a unique window into evolutionary scenarios for a dwarf planet tidally-activated by a giant planet. Triton is thus a window into, and an opportunity for, the next stage in Kuiper Belt dwarf planet exploration.

Triton’s young surface, with relatively few craters, stands out among moons in the Solar System and puts it in a class with Io, Europa, Enceladus, and Titan – other moons with geological processes active today. While error bars on the absolute crater model ages for Triton are large, they tell the story of a young, dynamic surface heavily modified by endogenic geologic processes. Crater counts suggest that Triton’s surface age is <100 Ma, possibly <10 Ma old (Stern and McKinnon, 2000; Schenk and Zahnle, 2007). Strong tidal heating anticipated from an ancient capture event would not
explain the currently observed young surface age, while more recent capture is unlikely (Noguiera et al., 2011). Theoretical models suggest that a subsurface liquid layer could be present today; thus Triton is a candidate ocean world (Hussman et al. 2006; Nimmo and Spencer, 2015).

Earth-based spectroscopy shows the presence of H$_2$O and CO$_2$, which are presumed to form the surface bedrock (Quirico et al. 1999; Grundy et al. 2010). Volatile ices N$_2$, CO, and CH$_4$ are present and are expected to migrate across the surface seasonally (Cruikshank et al. 1984; Cruikshank et al. 1993; Bauer et al. 2010; Buratti et al., 2011). HCN and C$_2$H$_6$ have been tentatively identified in earth-based spectra, and could result from photochemistry in the atmosphere (Burgdorf et al., 2010; Holler et al., 2016). Thus from Earth-based spectroscopy we know what is on the surface, but we do not know precisely where it is on the surface because Voyager did not carry a spectrometer capable of determining Triton’s surface composition and earth-based observations can only detect rough longitudinal variations in absorption signatures. Furthermore, the north polar region was hidden in the darkness of polar night. Many hypotheses for Triton’s unique geology invoke the behavior of volatiles. Surface composition of Triton and potential linkage to ocean chemistry represents a critical gap in our understanding of this outer Solar System moon.

In recent years the planetary science community has come to appreciate the importance of exploring ocean worlds - moons with subsurface liquid water. This paper applies that new perspective and assesses what we do and do not know about Triton in the context of answering the question “Is Triton an ocean world?” Further, as we explore ocean worlds, we ask “Do the oceans provide habitable environments and host life?” Liquid water, organic compounds, and chemical energy are generally accepted to be necessary ingredients for life (e.g., Cockell 2016; Hendrix et al. 2019). Telescopic observations of Triton’s surface and atmosphere reveal abundant elemental building blocks, especially carbon, hydrogen, oxygen and nitrogen (CHON), and suggest ionospheric production of organic compounds, which by analogy with Titan and Pluto could include materials of high chemical potential. Furthermore, Voyager 2 images provide tantalizing hints of exchange processes between Triton’s surface and subsurface. Confirmation of a rich organic-chemistry environment and ice-shell transport processes connecting Triton’s proposed ocean to its surface would place Triton among the highest value targets in the search for life, adding to the diversity of potentially habitable worlds, all the way out at 30 AU.
With this new appreciation of the importance of exploring ocean worlds, in the following sections we review the outstanding science questions, regarding Triton itself, its interaction with its ice giant planet, its probable ocean, and where it fits in the search for life. As a captured KBO Triton also has much to teach us about the early history of the Solar System and the evolution of large bodies in the Kuiper Belt. Voyager provided us with a snapshot in time (Figure 1), high resolution data on just one quarter of the surface: a teaser of the scientific riches still to be explored.

Figure 1. Voyager imaged the sub-Neptune side of Triton and discovered young terrain and erupting plumes. The colorful images suggest a variety of surface constituents; however without a near-infrared spectrometer Voyager was unable to identify the composition of surface units.

2. Triton’s Interior – Why do we regard Triton as a likely Ocean World?

Triton is a candidate ocean world based on its geologically young surface and inferred ongoing geological activity (see Section 3), its likelihood for having differentiated a hydrosphere from a rocky mantle, and
theoretical models that predict a long-lived ocean sustained by tidal heating.

Triton’s bulk composition indicates a rock:ice mass ratio of ~2 (McKinnon & Mueller, 1988; Tyler et al., 1989). Based on the extreme degree of tidal heating following capture, we expect that Triton has differentiated into a rocky core with a water ice mantle. Analysis of bodies with substantial rock content in their bulk composition led Hussman et al. (2006) to propose that formation of liquid layers on icy moons could be common from radiogenic heating of water laced with ammonia, which would depress the melting point. Although Triton’s orbit is now circular, a finite eccentricity immediately after capture would have resulted in tidal dissipation of heat, which could have been retained in the interior over geologic history, maintaining a liquid layer in the subsurface (Gaeman et al., 2012). Even in the absence of such antifreeze agents or of tidal heating, radiogenic heating alone could be sufficient to maintain an ocean. Additionally, although Triton’s orbit has long since circularized and eccentricity tides are negligible today, obliquity tides could be particularly strong on Triton because of its high inclination. These tides could potentially drive surface processes responsible for erasing craters; tidal heating would also help maintain the ocean (Nimmo and Spencer, 2015). Thermal evolution models by Nimmo & Spencer (2015) predict a present-day ice shell thickness of ~150 km above an ocean of similar thickness (see Figure 2).
Figure 2. Triton thermal evolution, redrafted from Nimmo & Spencer (2015), showing the evolution of the surface, radiogenic and ice-core interface heat fluxes (left-hand axis), and also the development of an ocean followed by the gradual thickening of the ice shell (right-hand axis). The heat from the primordial capture event has little effect/no on the present-day energy budget (Nimmo & Spencer, 2015).

Hammond et al. (2018) find that near-surface mixtures of ammonia and water can freeze and leave ammonia-rich ice below Triton’s surface that would facilitate cryovolcanism. Expulsion of ammonia from more slowly freezing ice beneath results in progressive enrichment in the remaining ocean’s ammonia content, reducing the rate of further freezing. Potentially cryovolcanic landforms on Triton’s surface are intriguing indicators of resurfacing (Croft et al. 1995).

The composition of Triton’s ocean depends on its volatile composition, expected to be cometary in nature (Shock and McKinnon 1993). Taking an average comet volatile composition as a reference (e.g., Mumma and Charnley 2011) yields an ocean rich in ammonium, sodium, bi/carbonate ions, and chloride (e.g., Castillo-Rogez et al. 2018). Sulfates are not expected to contribute to the ocean composition because sulfur is primarily in sulfide form (see McKinnon and Zolensky 2003; Neveu et al. 2017). However, recent
studies suggest sulfur could be released from a rocky mantle as a consequence of thermal metamorphism and potentially represent a late source of sulfates [Melwani Daswani et al. 2021]. Top-down freezing produces an outer shell dominated by ice while solutes concentrate in the ocean. Conditions in Triton’s shell are also consistent with the formation of clathrate hydrates (e.g., Kamata et al. 2019). Ocean material may be exposed on the surface via various mechanisms (e.g., convective upwelling, tectonics, impact-driven fracture opening) suggested at other icy moons.

**Strong evidence for the existence of a subsurface ocean on Triton needs to be confirmed, and validation that Triton is indeed an ocean world should be the primary objective of the next mission to Triton.**

3. Triton’s Geology and Surface Composition – Topography shaped by Cryovolcanism?

Voyager flew by Triton at an altitude of ~40,000 km. Although global coverage of the illuminated terrain was achieved over Triton’s 5.877 day rotation period, only the images of the Neptune-facing side south of ~40°N were acquired with spatial resolution of 1-3 km/line pair and allow geologic interpretation. At the time of the Voyager flyby Triton was experiencing an extreme southern spring, with a sub-solar latitude of 45°S, which meant that the northern hemisphere poleward of ~45°N was hidden in polar night.

The hemispheric mosaic (acquired at a ground sampling distance (GSD) of ~1400 to 600 m), and the highest resolution mosaic acquired at GSD of 420-325 m, shown in Figure 3, revealed exotic landforms unlike any on the moons of Jupiter, Saturn or Uranus. Cantaloupe terrain, walled plains, smooth plains, large endogenic (non-impact) pit chains, and guttae are among the many unique feature types imaged by Voyager, as summarized in Croft et al. (1995). Even landforms such as ridges, which may have analogues on other moons such as Europa’s double ridges (Prockter et al. 2005), have a different morphology on Triton: Triton’s ridges are an order of magnitude wider than Europa’s and at 100m height half as tall, and can have 3 to 4 parallel elements.

At the temperatures of the outer Solar System, water and CO₂ ices will generally behave as bedrock (e.g. Durham et al. 2010). The likely presence of other volatiles such as NH₃ and CH₃OH in the interior (Croft et al. 1995 and references therein) leads to the intriguing possibility that Triton’s geology shows examples of cryovolcanism and other exotic processes.
Cryovolcanism encompasses processes involving the deformation, intrusion, and extrusion of liquids, slushes and “warm” plastically deforming solids composed of mixtures of low-melting point materials” (Croft et al. 1995).

Figure 3. Many of Triton’s unique landforms suggest the possibility of cryovolcanism. The inset shows Mahilani plume erupting. Based on PIA00317. Credit: NASA/JPL/USGS.

Because geological features on Triton share characteristics with volcanic structures observed elsewhere in the Solar System, including Earth, cryovolcanism has been invoked as a plausible means of resurfacing on this enigmatic moon (Smith et al., 1989; Croft, 1995; Kargel and Strom, 1990; Schenk 1992). Voyager 2 imaged numerous candidate cryovolcanic features, most of which appear to have formed from, or to be associated with, the widespread extrusion of viscous fluids onto the surface. Candidate cryovolcanic features on Triton include: ring paterae, subcircular features 50-100 km in diameter which are defined by a scarp or a ring of coalescing pits, and may contain smooth plains material (Leviathan Patera being the most
prominent), which resemble terrestrial silicic calderas; pitted cones, small
conical hills typically 4-7 km in diameter with summit pits; and pit paterae,
circular to elongate non-impact depressions which may have raised rims, are
typically 10-20 km in diameter, may occur singly or in chains, and which are
associated with larger patches of smooth material.

Triton’s surface also exhibits cantaloupe terrain containing numerous
quasi-circular, closely-spaced shallow depressions called cavi. Cavi are
approximately 25-35 km in diameter with slightly raised rims, which are
interpreted to have formed from diapiric (or solid-state) upwelling of
subsurface material (Schenk and Jackson, 1993). Yet more enigmatic surface
features are the guttae and walled plains. Guttae are huge lobate features
that are 100-200 km across and are inferred to be at least tens of meters
wide. The smooth surfaces and lobate edges of the guttae suggest extrusive
materials that have flowed in a viscous manner. The dual albedo of these
features is highly unusual, and their bright aureoles may be representative
of low-viscosity fluids of a distinct composition, condensed volatiles that
were brought to the surface as the viscous guttae material erupted, or
surface materials that have undergone thermal metamorphosis (Croft et al.,
1995). The walled plains units of Tuonela and Ruach Planitia are subcircular
depressions that are 100-400 km in diameter, and appear to be filled with
smooth, relatively young plains material. Based on their morphological
similarity to terrestrial volcanic features, one interpretation of the walled
plains is that they are collapse calderas that were subsequently filled with
low-viscosity magmas; pits imaged on the floors of these units may represent
source vents from which the smooth material extruded (Croft et al., 1995).
Alternatively, the crenulate scarp margins of these plains could be a result
of sublimation erosion and scarp retreat; nitrogen is known to fill
topographic lows on Pluto, which has similar environmental conditions (e.g.,
Grundy et al., 2016). Scarp heights are up to 200-300 m.

The presence of these putative cryovolcanic constructs on the surface
suggests there have been times in Triton’s history when communication between
the surface and subsurface liquid reservoirs, possibly an ocean, occurred.
Bearing in mind Triton’s youthful surface, it is plausible that this
communication has persisted into current geological times.

Diapirism, driven by thermal and/or compositional gradients in Triton’s
crust, may be capable of bringing materials from the ice shell/ocean
interface to shallow levels in the crust (Hammond et al., 2018). In addition,
gradual freezing of the ice shell will also result in pressurization of the ocean underneath (Manga and Wang, 2007) and will help to promote the eruption of fluids to the surface. The effectiveness of this overpressurization depends on the satellite’s gravity; it is far more effective on Enceladus than Europa for example (Manga and Wang, 2007). Triton is an intermediate case, and the excess pressure may help the melt overcome the negative buoyancy relative to the ice shell. Conversely, excess pressurization caused by the gradual freezing of crustal fluid pockets could lead to stress conditions that promote fracturing in Triton’s ice shell. Cryovolcanic fluids could then be transported to the surface in these fractures. Such a scenario has been suggested for the transport of cryovolcanic fluids on Europa (Fagents, 2003).

Tectonic structures, and the patterns they make on planetary surfaces, can be used to identify the stress environment in which they formed (e.g. Kattenhorn & Hurford, 2009; Collins et al., 2010). Icy surfaces are dominated by extensional structures: the surface of Triton includes troughs, putative strike-slip faults and graben (Croft et al. 1995), and double-triple ridges (Prockter et al. 2005). The location and orientation of ridges and other smaller scale tectonic structures may outline a tectonic pattern that could be used to elucidate the stress mechanisms acting upon Triton’s icy shell as has been done at other icy moons (e.g. Greenberg et al. 1998). Stress mechanisms may occur at local, regional or global scales. The long length of double ridges on Triton indicates that a global scale stress mechanism is most likely. Candidate global-scale stress mechanisms may include diurnal obliquity tidal stress or nonsynchronous rotation (e.g. Kattenhorn & Hurford, 2009; Collins et al., 2010). Triton may be the only satellite where obliquity tides could dominate the stress environment and if stresses are high enough to fracture the ice shell, the predicted fracture patterns would be unique (Nimmo & Spencer, 2015). Nonsynchronous rotation may be at odds with the large apex-antapex asymmetry in crater populations (Zahnle et al. 2003); however these data only represent 30% of Triton’s surface.

Triton’s ridges, potentially diagnostic of the stress regime, are primarily formed in cantaloupe terrains. Many of Triton’s ridges resemble Europa’s double ridges (Prockter et al., 2005). There are differences however, perhaps related to modification processes on Triton. Collins and Schenk (1994, LPSC) and Croft et al. (1995) mapped the distribution of Triton’s ridges but did not find a clear correlation with common global stress mechanisms, in part because <40% of Triton has been imaged. Prockter
et al (2005) propose shear heating as a mechanism for forming Triton’s ridges, but these ridges form at multiple orientations and it is not clear a single mechanism can explain their morphology and distribution. Thus the origins of Triton’s ridges and relations to ridges on other icy worlds will remain unclear until global high-resolution mapping can be completed.

Regional or local-scale stress mechanisms may be related to smaller tectonic structures, mostly troughs, near the smooth plains and guttae. Higher-resolution imagery with near-global coverage is necessary to determine how widespread these smaller fractures are and validate the scale at which they are occurring and provide insight into whether these structures are driven by global or regional stresses.

Although limited to <20% of the surface, topographic constraints from limb profiles, stereogrammetry and photoclinometry all indicate that the relief on Triton globally is likely no more than 1 km (Thomas, 2000; Schenk et al., 2021 (this issue)). Low relief is consistent with the level of geologic activity and inferred high heat flow, as non-water-ice volatiles would tend to creep or viscously relax. Individual geologic features have relief of a few hundred meters, including the cantaloupe cavity which are 300-600 m deep (Schenk et al., 2021). The volcanic terrains east of the cantaloupe terrain are also of low relief of < 1 km. Interpretation of feature relief is hampered however, by the limited quantity and quality of the topographic data and by the lack of resolved spectroscopy and compositional mapping of the surface, as the stiffness and rheology of the icy shell is directly related to the amounts of ‘softer’ low-temperature ice phases within it.

While morphology is important, composition is a key test of formation hypotheses for Triton’s landforms. The compositions of Triton’s individual surface units are unknown because Voyager did not have an instrument that could map surface composition on Triton. Near-infrared (1–5 μm) spectral imaging provides a powerful tool for mapping surface compositions, and this wavelength region is especially well suited to Triton's distinctive suite of surface materials. Ices of H₂O, CO₂, CH₄, N₂, CO, etc. all have characteristic vibrational absorption features at these wavelengths, enabling them to be mapped remotely (e.g., Schmitt et al. 1998). Furthermore, the detailed shapes and locations of the absorptions are sensitive to the ice temperature, phase state, surface texture, and even the presence of rare isotopes and other impurities (Brown & Cruikshank 1997; Quirico & Schmitt 1997; Protopapa et al. 2015). These sensitivities provide rich opportunities to go beyond
just learning the composition of Triton's landforms, by obtaining additional
information about the thermal history and mechanical structure of surface
units. Thus near-infrared spectral imaging has the potential to resolve many
of Triton's long-standing scientific questions such as:

- Do guttae result from sublimation erosion or surface collapse over hot
  spots?
- Is cantaloupe terrain formed by diapirism?
- Are walled plains formed by the eruption of cryomagma?

For several decades, observers have studied Triton from Earth-based
telescopes at visible and near-infrared wavelengths. Earth-based
observations are unable to resolve specific geological features, but as
Triton spins on its axis with its 5.9 day period, different regions rotate
into and out of view, resulting in a cyclic pattern of subtle spectral
variations that has been used to place crude constraints on the global
distribution of ice (e.g., Grundy et al. 2010; Holler et al. 2016). It is
noteworthy that the most volatile of Triton's ices (N$_2$ and CO) show the
greatest amplitude in their variation as Triton spins on its axis, implying
that they are not confined to the region around the southern pole which is
continuously seen. The least volatile ices (H$_2$O and CO$_2$) show the least
variation, consistent with exposure at the pole, or else remarkably uniform
longitudinal distribution. Longer term, seasonal spectral changes are seen
too, but it is challenging to distinguish between effects of changing sub-
solar and sub-observer latitude and migration of volatile ices over seasonal
timescales (Bauer et al., 2010; Buratti et al. 2011). A few observatories
that provide the highest spatial resolutions such as Hubble Space Telescope
and 8 to 10 m telescopes with adaptive optics can resolve the disk of Triton
from Earth. But they only put a few resolution elements across the disk of
Triton, with resolution far too low to pick out specific landforms. Future
30 m class telescopes will do better, but still won't be able to address the
pressing questions about processes responsible for Triton's distinctive
landforms and their implications for the presence of an interior ocean.

By mapping the composition and morphology of Triton's surface units we
can address the overarching question “How does the interplay of tidal
dissipation, heat transfer, tectonics, cryovolcanism, diapirism, and surface-
atmosphere interactions drive resurfacing on Triton?”
4. Triton’s Atmosphere and Volatile Ices: Winds, Seasonal Processes and Climate

Triton’s atmosphere is predominantly composed of N$_2$ with traces of CH$_4$, CO, and other species (Cruikshank et al., 1984; Lellouch et al., 2010). Similar to Mars, which has a CO$_2$ atmosphere in vapor pressure equilibrium with CO$_2$ surface ice, Triton’s 1.4 Pa (in 1989) nitrogen atmosphere is in vapor pressure equilibrium with nitrogen surface ice at a temperature of 38K (Broadfoot et al. 1989; Tyler et al. 1989; Conrath et al. 1989; Ingersoll 1990). Nitrogen is expected to sublimate and condense seasonally, forming seasonal polar caps (Spencer 1990; Hansen and Paige, 1992). CO and CH$_4$ are minor constituents in the atmosphere and in surface ices; however, as observed on Pluto, these species should also move seasonally (Bertrand et al., in prep). Earth-based data from the decades since the Voyager flyby are consistent with N$_2$ sublimating away from the south pole, leaving longitudinally unchanging H$_2$O and CO$_2$, presumably the bedrock in the southern hemisphere (Quirico et al. 1999; Grundy et al. 2010; Holler et al. 2016).

However, some areal coverage of nitrogen-ice must persist on Triton’s illuminated surface for it to remain visible in Triton spectra.

Insolation, which drives surface ice energy balance with the atmosphere, and is controlled by the subsolar latitude, has a complex >600 year cycle due to the convolution of Triton’s inclined orbit with Neptune’s obliquity (Trafton 1984). The volatile transport driven by the changes in insolation throughout Triton’s year is expected to affect the atmospheric pressure (e.g., Hansen and Paige, 1992). Since the Voyager flyby in 1989 the subsolar point has passed through the southern summer solstice (at 50 S in 2001) and is now approaching the equator. Changes in Triton’s atmospheric pressure since the Voyager flyby have been detected in stellar occultations observed from Earth (e.g. Elliot 2000; Oliveira et al., 2021).

Many questions remain about the transport and distribution of Triton’s volatiles. What is the composition of Triton’s bright southern hemisphere terrain? Are the changes to Triton’s color detected telescopically and the ~latitudinal color bands imaged by Voyager (Figure 1) consistent with frost on the move seasonally (McEwen, 1990)? Are there permanent N$_2$ polar caps at both poles? Or conversely just one in the southern hemisphere (Moore and Spencer, 1990)? How much mass has been transferred into the northern polar region as ice in the southern hemisphere sublimated? At the time of the Voyager flyby the north polar region was dark, hidden in polar night. Just
the detection (or not) of a north polar N$_2$ cap will do much to inform volatile transport and climate models.

Voyager images showed discontinuous stretches of haze, illustrated in Figure 4 (Smith et al., 1989). Voyager UV solar occultation data showed that the haze layer extends up to ~30 km (Krasnopolsky et al., 1995). Similar to Pluto and Titan, haze production is expected from photochemistry of CH$_4$ in Triton’s atmosphere. Unlike Pluto, the colder temperatures and smaller mole fraction of CH$_4$ in Triton’s atmosphere means that the CH$_4$ is largely confined to lower altitudes and does not reach the exobase (Strobel and Zhu, 2017).

Ethane (DeMeo et al., 2010; Holler et al., 2016) and HCN (Gurwell et al., 2019) have tentatively been identified in earth-based spectra. In Triton’s cold atmosphere HCN and ethane grains could seed production of hydrocarbon ice particulates (Lavvas et al., 2020; Ohno et al., 2020), forming the haze, which would eventually precipitate onto the surface (Holler et al., 2016). Alternatively the haze could be made up of submicron N$_2$ ice particulates coming from seasonal sublimation and/or activity of plumes (Hillier & Veverka, 1994).

Superficially, since the atmospheres of both Triton and Pluto are predominantly composed of nitrogen with similar trace constituents one might expect similar thermal structure, haze layers, etc. In fact the two are quite different, and warrant further study (Strobel & Zhu, 2017).
Winds are driven by gas released as polar ice sublimates, as evidenced by the orientation of fan-shaped deposits on Triton’s surface and the orientation of Triton’s plumes (Hansen et al. 1990; Ingersoll, 1990). Geological evidence for winds may be revealed by the presence of dunes, like those of Pluto, and if so stratigraphic relations and geologic context of such aeolian landforms can further constrain relative ages of geologic events and geologic processes (Telfer et al., 2018; Ferrell et al., 2020). For example, dunes identified on Pluto are most prominent on the edges of glacial nitrogen convection cells near the opening of mountain valleys (Ferrell et al., 2020). These arrangements indicate youthful landforms (stratigraphically atop another youthful unit) and implicate orographically-related winds for their origins. Finding such evidence for such landforms and processes on Triton requires imaging the surface at better than a few hundred meter resolution.

A future mission to Triton that maps the now illuminated north polar region, surface ices, eolian landforms, and measures the density of the
atmosphere will illuminate Triton’s complex climate history, yielding new insights also applicable to Pluto and potentially other bodies in the Kuiper Belt with atmospheres.

5. Triton’s Plumes

At least two plumes erupting on Triton were observed with Voyager 2, the first active plumes to be discovered on an icy world (Smith et al., 1989; Soderblom et al., 1990). The plumes had long (~100 km), presumably windblown, clouds that were ~8 km above the surface, produced shadows, and varied over short intervals (< 1 hour) between encounter images (Soderblom et al., 1990). More than 120 dark fans on the southern hemisphere terrains were interpreted to be deposited on the surface by eruptions that were no longer active at the time images were taken by Voyager 2 (e.g., Hansen et al., 1990). See Figure 2. Reasoning that fans were unlikely to survive seasonal volatile transport a typical plume lifetime of 1 – 3 years was derived (Soderblom et al., 1990).

The plumes were initially hypothesized to be solar-powered eruptions: driven by seasonal sublimation of nitrogen under translucent ice (i.e., solid-state greenhouse heating), pressurization, and explosive venting (Kirk et al. 1995). This hypothesis was supported by the location of the plumes near the subsolar latitude during the Voyager 2 encounter and the location of the numerous dark streaks, presumably from former plumes, at latitudes corresponding to the subsolar track in the decades prior to the Voyager 2 encounter. All plumes and fans were confined to the bright southern hemisphere terrains, which were interpreted to be a cap of volatile ices, adding further support to a volatile-based hypothesis (Hansen et al., 1990).

The model of solar-powered activity has challenges, however, including the large size of the sub-ice nitrogen reservoir required (Kirk et al., 1995) and the apparent absence of analogous plumes and fans on Pluto (Hofgartner et al., 2018).

Brown and Kirk (1994) proposed an endogenic model where internal heat melts the base of a thick nitrogen-ice polar cap and the plumes result from exposure of the melt to the surface. A third hypothesis for Triton’s plumes is outgassing of its interior in the form of water-based cryovolcanism (Kirk et al., 1995). For many years, the conventional wisdom favored the solar-driven hypothesis; however, new datasets for the solar-driven jets of Mars and the endogenic plume of Enceladus lead us to re-examine the solar-driven...
hypothesis and ask whether the endogenic model might actually be the correct
one (Hansen and Kirk, 2015).

Table 1 compares the properties of the solar-driven seasonal jets at
Mars with Triton’s plumes and the endogenic plume of Enceladus.
Interestingly, the mass flux of Triton’s plumes is more similar to Enceladus
than Mars. These comparisons, of Triton to solar-driven eruptions on Mars
and Enceladus’ cryovolcanic plume, support a re-examination of the solar-
driven and endogenic hypotheses (Hansen and Kirk, 2015). The predicted thick
lithosphere (Section 2) is a challenge for an ocean-derived eruption, but if
the plumes are cryovolcanic they would be an important window into the
interior of this ocean world. Even if the plumes do not have an immediate
internal origin, it is likely that the material ejected as they erupt
originated in Triton’s interior, was frozen in the near-surface and
subsequently released.

Especially problematic is the lack of topographic and compositional
data and the difficulty of interpreting the geologic origins of the southern
hemisphere terrains from which the plumes erupt. Although relief in these
areas does not appear to be >1 km, the ruggedness and slopes in these regions
are unknown (Schenk et al., 2021), especially as no shadows were observed in
the Voyager imaging. The southern hemisphere terrains consist of areas of
irregular lobate patches of contrasting albedo and areas of irregular spots
and lineations, neither of which are currently interpretable. Whether the
plumes originate at the edges of or from within geologic units, or from
linear or point vent sources is unknown. Hence the mechanism of plume
venting is unconstrained at present.

The volatile reservoir that Triton’s plumes access will be revealed by
determining the energy source for the plumes from the distribution of active
plumes, and the composition of the deposits.

Table 1. Comparison of Plume Properties

| Parameter                        | Mars   | Triton         | Enceladus |
|----------------------------------|--------|----------------|-----------|
| Volatile erupting                | CO₂    | N₂ or H₂O      | H₂O       |
| Surface gravity (m sec⁻²)        | 3.72   | 0.779          | 0.113     |
| Plume height actual (km)         | 0.08   | 8              | 1500      |
| Plume height normalized to Triton gravity (km) | 2      | 8              | 60        |
| Source vent diameter (m)         | <1     | <3000          | ~9        |
| Exit velocity (m sec$^{-1}$) | 20 - 300 | 20 - 40 | 450 |
|-----------------------------|----------|--------|-----|
| Volatile storage (solar model) | 225 m$^3$ | 10 km$^3$ | n/a |
| Mass flux (vapor) | 150 gm/sec | Up to 400 kg/sec | 200 kg/sec |
| Mass flux (particles) | 30-150 gm/sec | <10 kg/sec | ~50 kg/sec |
| Temperature (K) | 140 | 38-42 | 76-170 |
| Eruption duration | <2 hr | 1 - 3 yrs | ongoing |

Notes on Table 1. Values in the column for Mars are from Thomas et al., 2011. Values for Triton are summarized in Kirk et al., 1995. Values for Enceladus are from Goguen et al., 2013 (source vent diameter and temperature), Hansen et al., 2020 (exit velocity and vapor mass flux), Ingersoll & Ewald, 2011 (particle mass flux).

6. Triton’s Unique Ionosphere and Interaction with Neptune’s magnetosphere

Voyager radio science observations revealed a significant ionosphere, with a well-defined peak at ~350 km altitude and peak densities of 2-5 x 10$^4$ cm$^{-3}$ (Tyler et al. 1989). Due to Neptune’s large distance from the Sun, such a strong ionosphere was not anticipated from solar photoionization alone, and it has therefore been suggested that precipitating electrons from Neptune’s magnetosphere are an important, and perhaps dominant, driver for Triton’s ionosphere (Krasnopolsky & Cruikshank, 1995; Majeed et al., 1990; Sittler & Hartle, 1996; Strobel et al., 1990; Yung & Lyons, 1990). However, due to Voyager 2’s distant (~40,000 km) flyby of Triton, there were no in-situ measurements made of Triton’s local magnetospheric environment. Therefore, the exact energy input from magnetospheric electrons to Triton’s ionosphere is poorly constrained, and it remains unconfirmed whether magnetospheric electrons are indeed the dominant ionization agent in Triton’s atmosphere.

Voyager 2 found that Neptune’s magnetosphere contains heavy ions with an inferred mass (10 – 40 Da, possibly N$^+$) and average temperature (60 – 100 eV, consistent with pick-up at Triton’s L-shell) that was consistent with a Triton source, and Sandel et al. (1990) suggested that a source of 1 kg/s from Triton’s atmosphere could explain the observed power of the Neptunian aurora. However, inconsistencies were later found between this inferred source rate and multiple Voyager 2 datasets (Decker & Cheng, 1994; Richardson et al., 1990). Thus, the exact role of Triton as a source of heavy ions to Neptune’s magnetosphere, and its role in generating Neptune’s aurora, remains unresolved.
Table 2: Local bulk plasma and magnetic field environment

| Triton Local Environment | Observed by Voyager 2 | References/Notes |
|--------------------------|-----------------------|------------------|
| **Plasma Density**       | Electrons: 0.0003 – 0.003 cm\(^{-3}\) | Zhang et al., 1991 |
|                          | Ions: 0.0015 cm\(^{-3}\) | Mauk et al., 1991 |
|                          |                      | Richardson et al., 1991 |
| **Plasma Temperature**   | 300 eV electrons     | Sittler and Hartle, 1996 |
|                          | 100 eV ions         | |
| **Plasma Composition**   | 50% N\(^+\)/50% H\(^+\) | Richardson and McNutt, 1990 |
|                          | \(<m> 7.5\) amu  | Mauk et al., 1991 |
| **Relative Plasma Speed**| 43 km/s              | Sittler and Hartle, 1996 |
| **Local Magnetic Field** | 5 – 11 nT            | Saur et al., 2010 |
| \(|B|\)                   |                      | |
| **Alfven Speed**         | > 800 km/s           | sub-Alfvénic & sub-magnetosonic |
| **N\(^+\) Gyroradius at**| 598 – 1315 km        | Too large for MHD treatment |
| **Triton**               |                      | |

Early modeling efforts suggested that Triton may have an Io (e.g. Strobel et al., 1990) or Venus-like (e.g. Sittler & Hartle, 1996) interaction with Neptune’s corotating magnetospheric plasma. However, without detailed in-situ measurements at Triton, the nature of this interaction remains largely unknown. Voyager 2 observed the bulk plasma density, temperature and composition throughout its encounter with Neptune, and found the plasma at Triton’s orbital distance to be quite diffuse, 0.003 particles/cm\(^3\), with temperatures of 100 eV, and composed of N\(^+\) and H\(^+\) in roughly equal parts (Sittler and Hartle, 1996). However, Triton was not close by when Voyager crossed at this orbital distance, and the plasma disk was crossed by the
spacecraft several Neptune radii away, leaving some uncertainty as to the variability and full characterization of Triton’s local environment. Table 2 summarizes the upstream environment near Triton’s orbit observed by Voyager 2. Measurements of hot plasma and energetic charged particles by the Voyager LECP instrument hinted to the fact that these populations appear to be strongly affected by Triton and/or interactions with the hypothetical Triton neutral torus, and that a distinct “trans-Triton” population of heavy energetic ions exists outside the minimum L-shell of Triton (Mauk et al., 1991).

Studying the plasma interaction between Triton and Neptune will give us new insights into the structure and chemistry of Triton’s upper atmosphere and ionosphere, and reveal how Triton loses material from its atmosphere and how this material interacts with Neptune’s magnetosphere.

7. How do we confirm that Triton is an Ocean World?

If Triton’s status as an ocean world can be confirmed the implications will be profoundly interesting. With its young surface Triton may join the group of moons that likely have transfer of material from their ocean to their surface: Europa, Enceladus, and Titan, and provide the first example of a confirmed ocean world with origins in the Kuiper belt. The confirmation of Triton’s ocean world status can be achieved in several ways.

Neptune’s magnetic field can be represented by an off-centered dipole that is tilted 46.8º relative to the planet’s spin axis (Ness et al., 1989; Connerney et al. 1991). Its 28.3º obliquity generates seasonal effects and, combined with the magnetic geometry, generates a strong diurnal variability of the magnetic field local to Triton with a 14-hour periodicity. Triton’s retrograde and highly inclined orbit (157º) also contributes a large amplitude local magnetic field variation creating a second 141-hour period wave. These magnetic waves and their harmonics in the rest frame of Triton are shown in Figure 5, which was modified from Saur et al. (2010). An internal ocean would produce an appreciable induced magnetic field (Saur et al. 2010) at these harmonics that could be detected from orbit or by a well-placed flyby (Nimmo and Pappalardo, 2016). Indeed, the abundance of solutes (in particular carbonates) expected in the ocean can increase electrical conductivity (EC) well above the EC resulting from the leaching of major elements from the rock phase as a consequence of aqueous alteration (i.e., 1-
7 S/m vs. <1 S/m, e.g., Leitner and Lunine 2019; Castillo-Rogez et al. in prep.) This contrasts with the low (<1 S/m) electrical conductivities estimated at Europa and Callisto from the Galileo magnetometer (Zimmer et al. 2000) and is explained by the lower abundances in carbon dioxide and ammonia accreted in these bodies, based on cosmochemical models (e.g., Kargel and Lunine 1998).

Figure 5. Neptune’s magnetic field at the location of Triton varies strongly with time and possesses harmonics at both the synodic rotation period of Neptune and the orbital period of Triton. Such harmonics can be exploited for induction sounding of an ocean in Triton from a single or multiple flybys of Triton. Figure modified from Saur et al. (2010).

Perhaps the most analogous ocean world detection to date has been that of Callisto orbiting Jupiter. Callisto is an icy ocean world, similar in size to Triton and in a similar plasma and magnetic field setting. Its ocean was detected using magnetic induction techniques from magnetic field measurements made by the Galileo spacecraft (Khurana et al., 1998; Kivelson et al., 1999; Zimmer et al., 2000). Callisto’s environment is similar in that there is a dominant magnetic field oscillation due to Jupiter’s dipole tilt, which causes a magnetic wave local to Callisto with an amplitude of ~ 40 nT (Saur et al., 2010). The Jovian plasma disk also oscillates up and down,
periodically sweeping over Callisto with enhanced plasma densities sourced from the Io plasma torus. It was determined that plasma interaction fields at Callisto would be too large to unambiguously detect an induction signal when Callisto was located in the Jovian plasma disk (Liuzzo et al., 2015, 2018), where the magnetic field is nearly orthogonal to the incident plasma flow of 192 km/s and the plasma density is relatively high (~0.15 particles/cm³). When Callisto was located outside the plasma disk and in the magnetospheric lobe, where plasma densities drop to between 0.04-0.06 particles/cm³, the plasma interaction fields, which scale with square root of the plasma density (Neubauer, 1980), were small and the induction signal was easier to identify. At Triton, the local plasma density is much lower than that experienced by Callisto, less than 0.003 particles/cm³ (Sittler and Hartle, 1996), and the relative plasma speed is also significantly lower at 43 km/s. Plasma interaction fields are thus not likely to contribute significantly to the observed magnetic perturbation. The likelihood of detecting Triton’s putative ocean using magnetic induction is therefore high, due to two large amplitude magnetic wave periods and a low density plasma environment.

Geodetic measurements could also be used to confirm the presence of an ocean on Triton. For instance, Triton’s predicted obliquity of 0.35° (Chen et al. 2014) would be larger if the surface were decoupled from the interior by an ocean, as is the case with Titan (Bills & Nimmo 2011). The responses of both the surface and gravity of Triton to obliquity tides will be extremely sensitive to the presence or absence of a subsurface ocean, as is the case at Europa (Moore & Schubert 2000). If the plumes of Triton are sampled (a daring dive to within 8 km of the surface) and shown to be salt-rich, as at Enceladus (Postberg et al. 2009), that would be strong evidence of subsurface liquid water interacting with the silicates. However, the geodetic measurements can distinguish between a regional sea and a global ocean, which chemical measurements cannot.

Adopting magnetic induction and geodetic measurements would enable the detection of a subsurface ocean if one exists on Triton. In combination, over several encounters or orbits, these measurement techniques would also enable characterization of the ocean’s depth, salinity, and the ice shell thickness.

8. Where Triton fits in the Search for Life Elsewhere in the Solar System
Today we ask: is there life anywhere else in our Solar System besides Earth? What conditions are required for life to appear and evolve? Do the oceans of moons of other planets provide habitable environments? A systematic sequence of investigations, from ocean identification to the search for life, forming an ocean world exploration strategy, was laid out by the Outer Planets Assessment Group (OPAG) Roadmaps to Ocean Worlds (ROW) team, and is illustrated in Figure 6, adapted from the ROW report (see also Hendrix et al., 2019).

As shown in Figure 6 we are furthest along in this endeavor at Enceladus, and the Europa Clipper mission and Titan Dragonfly will likewise advance our foundations at Europa and Titan, resp. In the coming years there may be missions to Enceladus and Europa searching for life. If we do not find life in either ocean we will ask why not?, and keep looking. If we do find life we will ask where else? Are all oceans hospitable to life? Do all hospitable oceans actually contain life?

Triton is a critical world as we seek to answer these questions – does life exist everywhere in the Solar Systems’ oceans? Or only in some oceans? To address these questions, and taking into account the long duration travel time to Neptune, the groundwork must be laid now. We must first ascertain with certainty whether or not Triton is an ocean world. We must then characterize the nature of its ocean and its accessibility – do cryovolcanic terrains and/or active plumes include ocean material? Are there cracks or faults or conduits with contact to the ocean reaching the surface? Is organic material generated in the tenuous atmosphere reaching this potential subsurface ocean?
Figure 6. ROW outlined a systematic process for exploration of ocean worlds and the search for life that begins with the identification of ocean worlds, followed by characterization of the ocean and assessment of its habitability.

What makes Triton such an interesting candidate? Objects formed in the outer Solar System are of particular interest for ocean world science because of their rich chemistry, including nitrogen compounds, which may be much less abundant in, e.g., the Galilean satellites. The hypothesized thermal diapirs that may transport fluids between Triton’s ocean and its surface, and that may play a key role in the formation of the cantaloupe terrain, may introduce chemical gradients in the ice shell and create habitable niches (Ruiz et al., 2007).

Figure 7 shows six key parameters related to the possibility of life, comparing Triton to Enceladus, Europa and Titan. The state of knowledge for each body is shown notionally; for example, all 4 are known to have water; however access of material from a subsurface ocean to the surface ranges from completely certain at Enceladus to very uncertain at Titan. Both Triton and Titan are known to have C, H, O and N, but ascertaining the presence of P and
S awaits the next mission(s). The oceans of Titan and Europa are substantial and long-lived, but Enceladus’ ocean may not be. Chemical energy refers to the production of organics – known with certainty for Titan’s haze, likely present in Enceladus’ plume (large molecules are detected but identification of which species is ambiguous), and expected from serpentinization at Europa.

Figure 7. This is a notional comparison of Triton to other known ocean worlds in terms of key parameters defining a body’s habitability potential. “Access” refers to one-way transfer of material from the ocean to the surface; “Exchange” refers to one-way transfer of material from the surface to the ocean. In the case of Triton, the state of knowledge is assessed from observations returned by Voyager 2 and geophysical modeling (see text for additional detail). Future knowledge of Triton is a hypothetical best case for a Triton flyby or Neptune-system mission.

Icy moons and dwarf planets may have begun as ocean worlds, and we suspect that some still are (see Hendrix et al. 2019 for review). With 150 large icy bodies (130 heliocentric plus 19 moons) with diameter > 400 km, the field is ripe for investigating their window for habitability. Hence, the
future exploration of Triton would not only explore the boundaries of
habitability in our Solar System, with application to other solar systems,
but also test the modalities of fundamental processes that determine the
habitability potential of icy bodies.

A future mission to Triton would test the habitability potential of a
body formed at 40 AU, similar to Pluto in terms of chemistry but likely
benefiting from both initial and long-lived tidal heating.

9. Future Missions to Triton (and Neptune)

Given that we know so little about Triton a single flyby would yield
major scientific rewards as evidenced for example by New Horizons’ flyby
reconnaissance of Pluto and Charon. The most important scientific questions
to answer at Triton are (1) whether or not it has a subsurface ocean and (2)
whether or not that ocean is exchanging material with the surface. A flyby
mission such as the Discovery mission Trident (Prockter et al. 2019) could
use magnetic induction to determine whether or not Triton has a deep liquid
layer, i.e. whether or not Triton is an ocean world. A flyby mission
carrying modern instruments much more capable than the Voyager payload could
image the side of Triton not imaged by Voyager, terra incognita in the
northern hemisphere, and study Triton’s interior structure (e.g., determine
the extent of physical differentiation), surface ices, atmosphere, the energy
powering its plumes, and drivers for Triton’s intense ionosphere. Simply by
carrying an imaging infrared spectrometer and mapping the composition of
Triton’s surface units a flyby mission would answer numerous fundamental
questions about exotic cryovolcanic processes.

A Flagship mission in orbit around Neptune, such as the recent Neptune
Odyssey planetary mission concept study [Rymer et al., 2020a,b], would yield
Cassini-level scientific return on the entire ice giant system as well as
both broader and more in-depth investigations of Triton itself. An orbiter
with a robust modern payload performing multiple Triton flybys offers the
opportunity to do comprehensive photogeologic and spectral mapping of
Triton’s surface and volatile distribution, probe the deep interior of Triton
from electromagnetic sounding and geodesy, and to study time domain
variability of Triton’s atmosphere, magnetosphere, and surface. It could
also adapt to new discoveries to further investigate Triton, just as, for
example, Cassini did at Enceladus and Titan. Compiling observations from
multiple flybys of Triton also enables comprehensive characterization (e.g., salinity and thickness) of the likely subsurface ocean, necessary for ascertaining habitability. A Neptune system orbiter could answer Triton science questions, and is the key to unlocking our understanding of both ice giants and to making the next major advance in Kuiper Belt dwarf planet science.

The Trident and Odyssey mission concepts can be thought of as two ends of a spectrum of possible missions, depending on available funding. A Discovery mission is focused on the most important science goals while a flagship can be comprehensive and address the entire system. In the case of a dynamic world like Triton the combination of the two missions in sequence is complementary. Together they enable the study of diurnal to decadal temporal elements of change in what is already known to be a dynamic environment. As an example, with a long temporal baseline, the following questions could be addressed: How much do Triton’s ices migrate as the subsolar point moves steadily northward? Are there any surface changes as a result of cryovolcanism? What changes in the climate are observed?

The final argument for a mission to Triton comes from the broader community, in the form of the OPAG **Roadmap to Ocean Worlds (ROW)** recommendation: Among the candidate ocean worlds in the Solar System “Triton is deemed the highest priority target to address as part of an Ocean Worlds Program. This priority is given based on the extraordinary hints of activity shown by the Voyager spacecraft (e.g., plume activity; smooth, walled plains units; the cantaloupe terrain suggestive of convection) and the potential for ocean-driven activity given by Cassini results at Enceladus. Although the source of energy for Triton’s activity remains unclear, all active bodies in the Solar System are driven by endogenic heat sources, and Triton’s activity coupled with the young surface age makes investigation of an endogenic source important.” (Hendrix and Hurford, 2019).

Based on ROW’s recommendation OPAG placed a Neptune flagship orbiter as its highest priority mission for the next decade (Moore and OPAG, 2020).

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