

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

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Short Title: Triton, a Candidate Ocean World

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7 **Abstract**
8

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

24 Neptune's moon Triton has been explored by just one spacecraft, Voyager
25 2, in 1989. Images revealed a unique geologically young surface with
26 landforms not found anywhere else in the Solar System (Smith et al. 1989).
27 Plumes erupt from a surface with a temperature of just 38K (Conrath et al.
28 1989). A tenuous nitrogen atmosphere is in vapor pressure equilibrium with
29 its surface ices, similar to Pluto (Broadfoot et al. 1989; Tyler et al. 1989;
30 Stern et al. 2018). Triton is also noteworthy for its retrograde, highly
31 inclined orbit, making it almost certainly a captured Kuiper Belt dwarf
32 planet, with a differentiated interior heated by tidal braking (McKinnon et
33 al. 1995; Agnor and Hamilton 2006). Triton, nearly a twin in size to Pluto,
34 provides a unique window into evolutionary scenarios for a dwarf planet
35 tidally-activated by a giant planet. Triton is thus a window into, and an
36 opportunity for, the next stage in Kuiper Belt dwarf planet exploration.

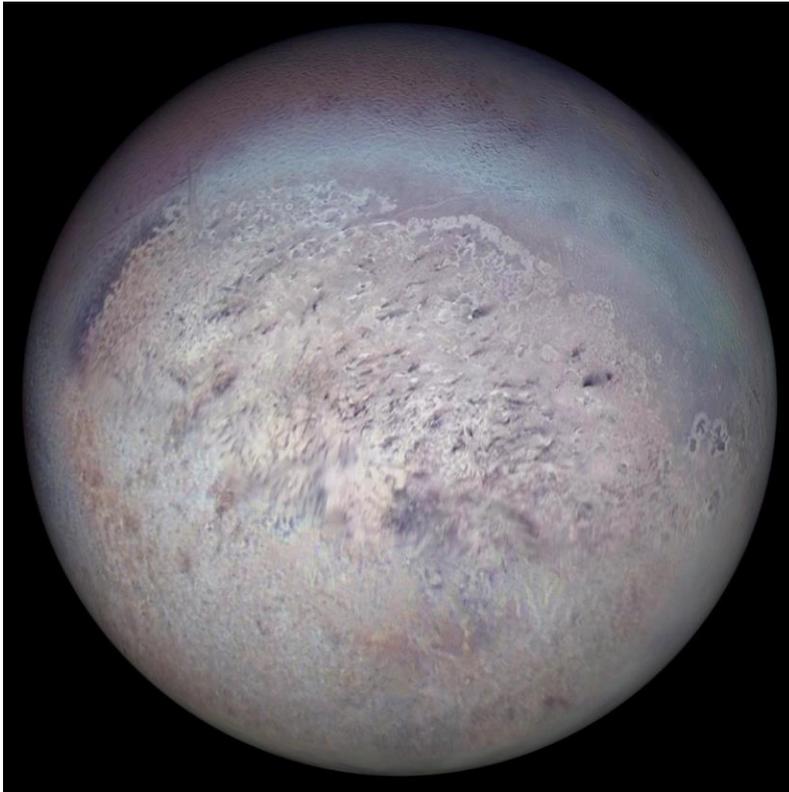
37 Triton's young surface, with relatively few craters, stands out among
38 moons in the Solar System and puts it in a class with Io, Europa, Enceladus,
39 and Titan - other moons with geological processes active today. While error
40 bars on the absolute crater model ages for Triton are large, they tell the
41 story of a young, dynamic surface heavily modified by endogenic geologic
42 processes. Crater counts suggest that Triton's surface age is <100 Ma,
43 possibly <10 Ma old (Stern and McKinnon, 2000; Schenk and Zahnle, 2007).
44 Strong tidal heating anticipated from an ancient capture event would not

45 explain the currently observed young surface age, while more recent capture
46 is unlikely (Noguiera et al., 2011). Theoretical models suggest that a
47 subsurface liquid layer could be present today; thus Triton is a candidate
48 ocean world (Hussman et al. 2006; Nimmo and Spencer, 2015).

49 Earth-based spectroscopy shows the presence of H₂O and CO₂, which are
50 presumed to form the surface bedrock (Quirico et al. 1999; Grundy et al.
51 2010). Volatile ices N₂, CO, and CH₄ are present and are expected to migrate
52 across the surface seasonally (Cruikshank et al., 1984; Cruikshank et al.
53 1993; Bauer et al., 2010; Buratti et al., 2011). HCN and C₂H₆ have been
54 tentatively identified in earth-based spectra, and could result from
55 photochemistry in the atmosphere (Burgdorf et al., 2010; Holler et al.,
56 2016). Thus from Earth-based spectroscopy we know *what* is on the surface,
57 but we do not know precisely *where* it is on the surface because Voyager did
58 not carry a spectrometer capable of determining Triton's surface composition
59 and earth-based observations can only detect rough longitudinal variations in
60 absorption signatures. Furthermore, the north polar region was hidden in the
61 darkness of polar night. Many hypotheses for Triton's unique geology invoke
62 the behavior of volatiles. Surface composition of Triton and potential
63 linkage to ocean chemistry represents a critical gap in our understanding of
64 this outer Solar System moon.

65 In recent years the planetary science community has come to appreciate
66 the importance of exploring ocean worlds - moons with subsurface liquid
67 water. This paper applies that new perspective and assesses what we do and
68 do not know about Triton in the context of answering the question "*Is Triton*
69 *an ocean world?*" Further, as we explore ocean worlds, we ask "Do the oceans
70 provide habitable environments and host life?" Liquid water, organic
71 compounds, and chemical energy are generally accepted to be necessary
72 ingredients for life (e.g., Cockell 2016; Hendrix et al. 2019). Telescopic
73 observations of Triton's surface and atmosphere reveal abundant elemental
74 building blocks, especially carbon, hydrogen, oxygen and nitrogen (CHON), and
75 suggest ionospheric production of organic compounds, which by analogy with
76 Titan and Pluto could include materials of high chemical potential.
77 Furthermore, Voyager 2 images provide tantalizing hints of exchange processes
78 between Triton's surface and subsurface. Confirmation of a rich organic-
79 chemistry environment and ice-shell transport processes connecting Triton's
80 proposed ocean to its surface would place Triton among the highest value
81 targets in the search for life, adding to the diversity of potentially
82 habitable worlds, all the way out at 30 AU.

83 With this new appreciation of the importance of exploring ocean worlds,
84 in the following sections we review the outstanding science questions,
85 regarding Triton itself, its interaction with its ice giant planet, its
86 probable ocean, and where it fits in the search for life. As a captured KBO
87 Triton also has much to teach us about the early history of the Solar System
88 and the evolution of large bodies in the Kuiper Belt. Voyager provided us
89 with a snapshot in time (Figure 1), high resolution data on just one quarter
90 of the surface: a teaser of the *scientific riches still to be explored*.
91



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93
94 *Figure 1. Voyager imaged the sub-Neptune side of Triton and discovered young*
95 *terrain and erupting plumes. The colorful images suggest a variety of*
96 *surface constituents; however without a near-infrared spectrometer Voyager*
97 *was unable to identify the composition of surface units.*

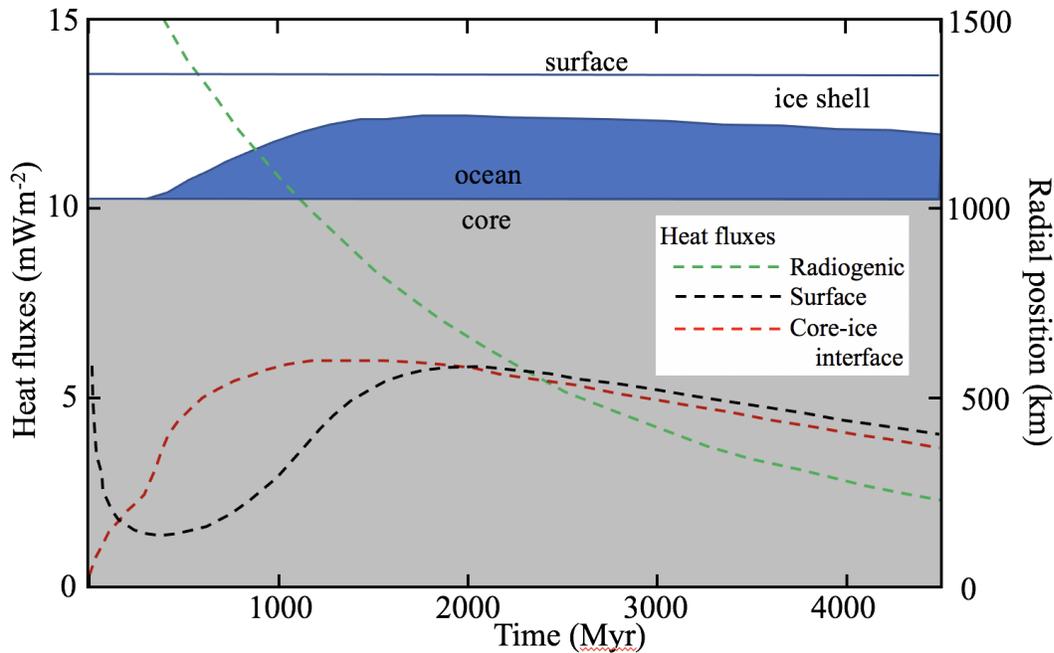
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99 **2. Triton's Interior - Why do we regard Triton as a likely Ocean World?**

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101 Triton is a candidate ocean world based on its geologically young
102 surface and inferred ongoing geological activity (see Section 3), its
103 likelihood for having differentiated a hydrosphere from a rocky mantle, and

104 theoretical models that predict a long-lived ocean sustained by tidal
105 heating.

106 Triton's bulk composition indicates a rock:ice mass ratio of ~ 2
107 (McKinnon & Mueller, 1988; Tyler et al., 1989). Based on the extreme degree
108 of tidal heating following capture, we expect that Triton has differentiated
109 into a rocky core with a water ice mantle. Analysis of bodies with
110 substantial rock content in their bulk composition led Hussman et al. (2006)
111 to propose that formation of liquid layers on icy moons could be common from
112 radiogenic heating of water laced with ammonia, which would depress the
113 melting point. Although Triton's orbit is now circular, a finite eccentricity
114 immediately after capture would have resulted in tidal dissipation of heat,
115 which could have been retained in the interior over geologic history,
116 maintaining a liquid layer in the subsurface (Gaeman et al., 2012). Even in
117 the absence of such antifreeze agents or of tidal heating, radiogenic heating
118 alone could be sufficient to maintain an ocean. Additionally, although
119 Triton's orbit has long since circularized and eccentricity tides are
120 negligible today, obliquity tides could be particularly strong on Triton
121 because of its high inclination. These tides could potentially drive surface
122 processes responsible for erasing craters; tidal heating would also help
123 maintain the ocean (Nimmo and Spencer, 2015). Thermal evolution models by
124 Nimmo & Spencer (2015) predict a present-day ice shell thickness of ~ 150 km
125 above an ocean of similar thickness (see Figure 2).

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129 *Figure 2. Triton thermal evolution, redrafted from Nimmo & Spencer (2015),*
 130 *showing the evolution of the surface, radiogenic and ice-core interface heat*
 131 *fluxes (left-hand axis), and also the development of an ocean followed by the*
 132 *gradual thickening of the ice shell (right-hand axis). The heat from the*
 133 *primordial capture event has little effect/no on the present-day energy*
 134 *budget (Nimmo & Spencer, 2015).*

135

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

143

144 The composition of Triton's ocean depends on its volatile composition,
 145 expected to be cometary in nature (Shock and McKinnon 1993). Taking an
 146 average comet volatile composition as a reference (e.g., Mumma and Charnley
 147 2011) yields an ocean rich in ammonium, sodium, bi/carbonate ions, and
 148 chloride (e.g., Castillo-Rogez et al. 2018). Sulfates are not expected to
 149 contribute to the ocean composition because sulfur is primarily in sulfide
 form (see McKinnon and Zolensky 2003; Neveu et al. 2017). However, recent

150 studies suggest sulfur could be released from a rocky mantle as a consequence
151 of thermal metamorphism and potentially represent a late source of sulfates
152 [Melwani Daswani et al. 2021]. Top-down freezing produces an outer shell
153 dominated by ice while solutes concentrate in the ocean. Conditions in
154 Triton's shell are also consistent with the formation of clathrate hydrates
155 (e.g., Kamata et al. 2019). Ocean material may be exposed on the surface via
156 various mechanisms (e.g., convective upwelling, tectonics, impact-driven
157 fracture opening) suggested at other icy moons.

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

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163 **3. Triton's Geology and Surface Composition – Topography shaped by** 164 **Cryovolcanism?**

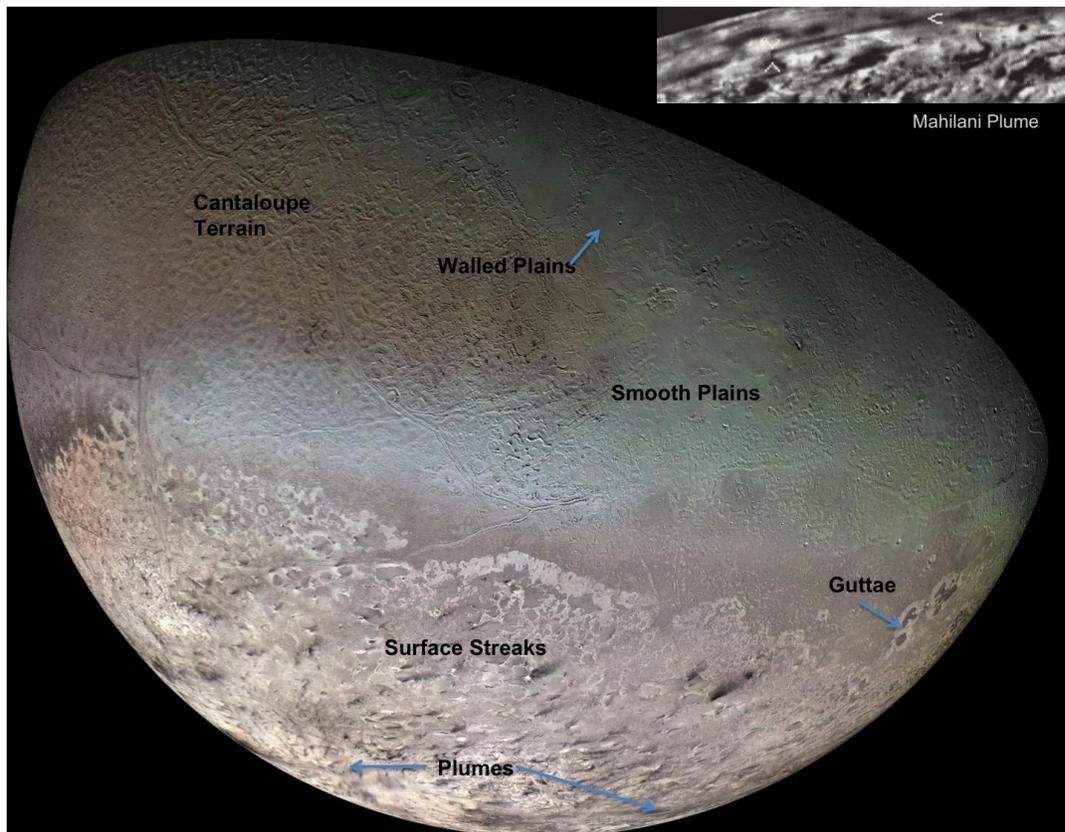
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166 Voyager flew by Triton at an altitude of ~40,000 km. Although global
167 coverage of the illuminated terrain was achieved over Triton's 5.877 day
168 rotation period, only the images of the Neptune-facing side south of ~40°N
169 were acquired with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

173 The hemispheric mosaic (acquired at a ground sampling distance (GSD) of
174 ~1400 to 600 m), and the highest resolution mosaic acquired at GSD of 420-325
175 m, shown in Figure 3, revealed exotic landforms unlike any on the moons of
176 Jupiter, Saturn or Uranus. Cantaloupe terrain, walled plains, smooth plains,
177 large endogenic (non-impact) pit chains, and guttae are among the many unique
178 feature types imaged by Voyager, as summarized in Croft et al. (1995). Even
179 landforms such as ridges, which may have analogues on other moons such as
180 Europa's double ridges (Prockter et al. 2005), have a different morphology on
181 Triton: Triton's ridges are an order of magnitude wider than Europa's and at
182 100m height half as tall, and can have 3 to 4 parallel elements.

183 At the temperatures of the outer Solar System, water and CO₂ ices will
184 generally behave as bedrock (e.g. Durham et al. 2010). The likely presence
185 of other volatiles such as NH₃ and CH₃OH in the interior (Croft et al. 1995
186 and references therein) leads to the intriguing possibility that Triton's
187 geology shows examples of cryovolcanism and other exotic processes.

188 ["Cryovolcanism encompasses processes involving the deformation, intrusion,
189 and extrusion of liquids, slushes and "warm" plastically deforming solids
190 composed of mixtures of low-melting point materials" (Croft et al. 1995).]
191



192
193 **Figure 3.** Many of Triton's unique landforms suggest the possibility of
194 cryovolcanism. The inset shows Mahilani plume erupting. Based on PIA00317.
195 Credit: NASA/JPL/USGS.
196
197

198 Because geological features on Triton share characteristics with
199 volcanic structures observed elsewhere in the Solar System, including Earth,
200 cryovolcanism has been invoked as a plausible means of resurfacing on this
201 enigmatic moon (Smith et al., 1989; Croft, 1995; Kargel and Strom, 1990;
202 Schenk 1992). Voyager 2 imaged numerous candidate cryovolcanic features,
203 most of which appear to have formed from, or to be associated with, the
204 widespread extrusion of viscous fluids onto the surface. Candidate
205 cryovolcanic features on Triton include: *ring paterae*, subcircular features
206 50-100 km in diameter which are defined by a scarp or a ring of coalescing
207 pits, and may contain smooth plains material (Leviathan Patera being the most

208 prominent), which resemble terrestrial silicic calderas; *pitted cones*, small
209 conical hills typically 4-7 km in diameter with summit pits; and *pit paterae*,
210 circular to elongate non-impact depressions which may have raised rims, are
211 typically 10-20 km in diameter, may occur singly or in chains, and which are
212 associated with larger patches of smooth material.

213 Triton's surface also exhibits cantaloupe terrain containing numerous
214 quasi-circular, closely-spaced shallow depressions called *cavi*. *Cavi* are
215 approximately 25-35 km in diameter with slightly raised rims, which are
216 interpreted to have formed from diapiric (or solid-state) upwelling of
217 subsurface material (Schenk and Jackson, 1993). Yet more enigmatic surface
218 features are the *guttae* and *walled plains*. *Guttae* are huge lobate features
219 that are 100-200 km across and are inferred to be at least tens of meters
220 thick. These features are surrounded by bright aureoles that are 20-30 km
221 wide. The smooth surfaces and lobate edges of the *guttae* suggest extrusive
222 materials that have flowed in a viscous manner. The dual albedo of these
223 features is highly unusual, and their bright aureoles may be representative
224 of low-viscosity fluids of a distinct composition, condensed volatiles that
225 were brought to the surface as the viscous *guttae* material erupted, or
226 surface materials that have undergone thermal metamorphosis (Croft et al.,
227 1995). The *walled plains* units of Tuonela and Ruach Planitia are subcircular
228 depressions that are 100-400 km in diameter, and appear to be filled with
229 smooth, relatively young plains material. Based on their morphological
230 similarity to terrestrial volcanic features, one interpretation of the *walled*
231 *plains* is that they are collapse calderas that were subsequently filled with
232 low-viscosity magmas; pits imaged on the floors of these units may represent
233 source vents from which the smooth material extruded (Croft et al., 1995).
234 Alternatively, the crenulate scarp margins of these plains could be a result
235 of sublimation erosion and scarp retreat; nitrogen is known to fill
236 topographic lows on Pluto, which has similar environmental conditions (e.g.,
237 Grundy et al., 2016). Scarp heights are up to 200-300 m.

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

243 Diapirism, driven by thermal and/or compositional gradients in Triton's
244 crust, may be capable of bringing materials from the ice shell/ocean
245 interface to shallow levels in the crust (Hammond et al., 2018). In addition,

246 gradual freezing of the ice shell will also result in pressurization of the
247 ocean underneath (Manga and Wang, 2007) and will help to promote the eruption
248 of fluids to the surface. The effectiveness of this overpressurization
249 depends on the satellite's gravity; it is far more effective on Enceladus
250 than Europa for example (Manga and Wang, 2007). Triton is an intermediate
251 case, and the excess pressure may help the melt overcome the negative
252 buoyancy relative to the ice shell. Conversely, excess pressurization caused
253 by the gradual freezing of crustal fluid pockets could lead to stress
254 conditions that promote fracturing in Triton's ice shell. Cryovolcanic fluids
255 could then be transported to the surface in these fractures. Such a scenario
256 has been suggested for the transport of cryovolcanic fluids on Europa
257 (Fagents, 2003).

258 Tectonic structures, and the patterns they make on planetary surfaces,
259 can be used to identify the stress environment in which they formed (e.g.
260 Kattenhorn & Hurford, 2009; Collins et al., 2010). Icy surfaces are dominated
261 by extensional structures: the surface of Triton includes troughs, putative
262 strike-slip faults and graben (Croft et al. 1995), and double-triple ridges
263 (Prockter et al. 2005). The location and orientation of ridges and other
264 smaller scale tectonic structures may outline a tectonic pattern that could
265 be used to elucidate the stress mechanisms acting upon Triton's icy shell as
266 has been done at other icy moons (e.g. Greenberg et al. 1998). Stress
267 mechanisms may occur at local, regional or global scales. The long length of
268 double ridges on Triton indicates that a global scale stress mechanism is
269 most likely. Candidate global-scale stress mechanisms may include diurnal
270 obliquity tidal stress or nonsynchronous rotation (e.g. Kattenhorn & Hurford,
271 2009; Collins et al., 2010). Triton may be the only satellite where obliquity
272 tides could dominate the stress environment and if stresses are high enough
273 to fracture the ice shell, the predicted fracture patterns would be unique
274 (Nimmo & Spencer, 2015). Nonsynchronous rotation may be at odds with the
275 large apex-antapex asymmetry in crater populations (Zahnle et al. 2003);
276 however these data only represent 30% of Triton's surface.

277 Triton's ridges, potentially diagnostic of the stress regime, are
278 primarily formed in cantaloupe terrains. Many of Triton's ridges resemble
279 Europa's double ridges (Prockter et al., 2005). There are differences
280 however, perhaps related to modification processes on Triton. Collins and
281 Schenk (1994, LPSC) and Croft et al. (1995) mapped the distribution of
282 Triton's ridges but did not find a clear correlation with common global
283 stress mechanisms, in part because <40% of Triton has been imaged. Prockter

284 et al (2005) propose shear heating as a mechanism for forming Triton's
285 ridges, but these ridges form at multiple orientations and it is not clear a
286 single mechanism can explain their morphology and distribution. Thus the
287 origins of Triton's ridges and relations to ridges on other icy worlds will
288 remain unclear until global high-resolution mapping can be completed.

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

295 Although limited to <20% of the surface, topographic constraints from
296 limb profiles, stereogrammetry and photoclinometry all indicate that the
297 relief on Triton globally is likely no more than 1 km (Thomas, 2000; Schenk
298 et al., 2021 (this issue)). Low relief is consistent with the level of
299 geologic activity and inferred high heat flow, as non-water-ice volatiles
300 would tend to creep or viscously relax. Individual geologic features have
301 relief of a few hundred meters, including the cantaloupe cavi which are 300-
302 600 m deep (Schenk et al., 2021). The volcanic terrains east of the
303 cantaloupe terrain are also of low relief of < 1km. Interpretation of
304 feature relief is hampered however, by the limited quantity and quality of
305 the topographic data and by the lack of resolved spectroscopy and
306 compositional mapping of the surface, as the stiffness and rheology of the
307 icy shell is directly related to the amounts of 'softer' low-temperature ice
308 phases within it.

309 While morphology is important, *composition is a key test of formation*
310 *hypotheses for Triton's landforms*. The compositions of Triton's individual
311 surface units are unknown because Voyager did not have an instrument that
312 could map surface composition on Triton. Near-infrared (1-5um) spectral
313 imaging provides a powerful tool for mapping surface compositions, and this
314 wavelength region is especially well suited to Triton's distinctive suite of
315 surface materials. Ices of H₂O, CO₂, CH₄, N₂, CO, etc. all have characteristic
316 vibrational absorption features at these wavelengths, enabling them to be
317 mapped remotely (e.g., Schmitt et al. 1998). Furthermore, the detailed
318 shapes and locations of the absorptions are sensitive to the ice temperature,
319 phase state, surface texture, and even the presence of rare isotopes and
320 other impurities (Brown & Cruikshank 1997; Quirico & Schmitt 1997; Protopapa
321 et al. 2015). These sensitivities provide rich opportunities to go beyond

322 just learning the composition of Triton's landforms, by obtaining additional
323 information about the thermal history and mechanical structure of surface
324 units. Thus near-infrared spectral imaging has the potential to resolve many
325 of Triton's long-standing scientific questions such as:

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

330

331 For several decades, observers have studied Triton from Earth-based
332 telescopes at visible and near-infrared wavelengths. Earth-based
333 observations are unable to resolve specific geological features, but as
334 Triton spins on its axis with its 5.9 day period, different regions rotate
335 into and out of view, resulting in a cyclic pattern of subtle spectral
336 variations that has been used to place crude constraints on the global
337 distribution of ice (e.g., Grundy et al. 2010; Holler et al. 2016). It is
338 noteworthy that the most volatile of Triton's ices (N_2 and CO) show the
339 greatest amplitude in their variation as Triton spins on its axis, implying
340 that they are not confined to the region around the southern pole which is
341 continuously seen. The least volatile ices (H_2O and CO_2) show the least
342 variation, consistent with exposure at the pole, or else remarkably uniform
343 longitudinal distribution. Longer term, seasonal spectral changes are seen
344 too, but it is challenging to distinguish between effects of changing sub-
345 solar and sub-observer latitude and migration of volatile ices over seasonal
346 timescales (Bauer et al., 2010; Buratti et al. 2011). A few observatories
347 that provide the highest spatial resolutions such as Hubble Space Telescope
348 and 8 to 10 m telescopes with adaptive optics can resolve the disk of Triton
349 from Earth. But they only put a few resolution elements across the disk of
350 Triton, with resolution far too low to pick out specific landforms. Future
351 30 m class telescopes will do better, but still won't be able to address the
352 pressing questions about processes responsible for Triton's distinctive
353 landforms and their implications for the presence of an interior ocean.

354 *By mapping the composition and morphology of Triton's surface units we*
355 *can address the overarching question "How does the interplay of tidal*
356 *dissipation, heat transfer, tectonics, cryovolcanism, diapirism, and surface-*
357 *atmosphere interactions drive resurfacing on Triton?"*

358

359

360 **4. Triton's Atmosphere and Volatile Ices: Winds, Seasonal Processes and**
361 **Climate**

362

363 Triton's atmosphere is predominantly composed of N₂ with traces of CH₄,
364 CO, and other species (Cruikshank et al., 1984; Lellouch et al., 2010).
365 Similar to Mars, which has a CO₂ atmosphere in vapor pressure equilibrium with
366 CO₂ surface ice, Triton's 1.4 Pa (in 1989) nitrogen atmosphere is in vapor
367 pressure equilibrium with nitrogen surface ice at a temperature of 38K
368 (Broadfoot et al. 1989; Tyler et al. 1989; Conrath et al. 1989; Ingersoll
369 1990). Nitrogen is expected to sublime and condense seasonally, forming
370 seasonal polar caps (Spencer 1990; Hansen and Paige, 1992). CO and CH₄ are
371 minor constituents in the atmosphere and in surface ices; however, as
372 observed on Pluto, these species should also move seasonally (Bertrand et
373 al., in prep). Earth-based data from the decades since the Voyager flyby are
374 consistent with N₂ sublimating away from the south pole, leaving
375 longitudinally unchanging H₂O and CO₂, presumably the bedrock in the southern
376 hemisphere (Quirico et al. 1999; Grundy et al. 2010; Holler et al. 2016).
377 However, some areal coverage of nitrogen-ice must persist on Triton's
378 illuminated surface for it to remain visible in Triton spectra.

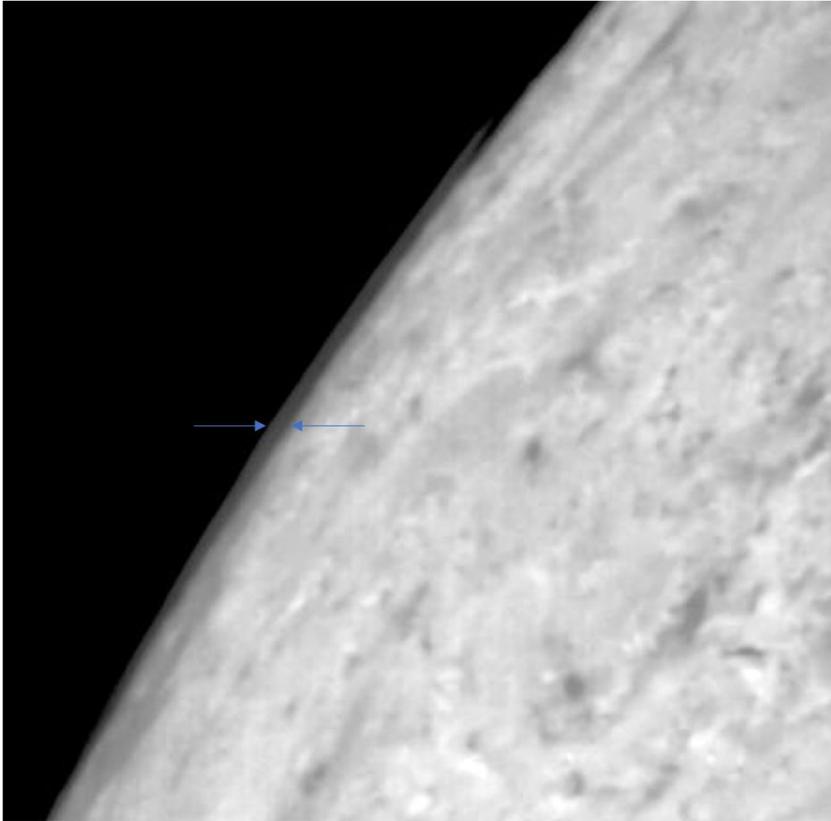
379 Insolation, which drives surface ice energy balance with the
380 atmosphere, and is controlled by the subsolar latitude, has a complex >600
381 year cycle due to the convolution of Triton's inclined orbit with Neptune's
382 obliquity (Trafton 1984). The volatile transport driven by the changes in
383 insolation throughout Triton's year is expected to affect the atmospheric
384 pressure (e.g., Hansen and Paige, 1992). Since the Voyager flyby in 1989 the
385 subsolar point has passed through the southern summer solstice (at 50 S in
386 2001) and is now approaching the equator. Changes in Triton's atmospheric
387 pressure since the Voyager flyby have been detected in stellar occultations
388 observed from Earth (e.g. Elliot 2000; Oliveira et al., 2021).

389 Many questions remain about the transport and distribution of Triton's
390 volatiles. What is the composition of Triton's bright southern hemisphere
391 terrain? Are the changes to Triton's color detected telescopically and the
392 ~latitudinal color bands imaged by Voyager (Figure 1) consistent with frost
393 on the move seasonally (McEwen, 1990)? Are there permanent N₂ polar caps at
394 both poles? Or conversely just one in the southern hemisphere (Moore and
395 Spencer, 1990)? How much mass has been transferred into the northern polar
396 region as ice in the southern hemisphere sublimated? At the time of the
397 Voyager flyby the north polar region was dark, hidden in polar night. Just

398 the detection (or not) of a north polar N₂ cap will do much to inform volatile
399 transport and climate models.

400 Voyager images showed discontinuous stretches of haze, illustrated in
401 Figure 4 (Smith et al., 1989). Voyager UV solar occultation data showed that
402 the haze layer extends up to ~30 km (Krasnopolsky et al., 1995). Similar to
403 Pluto and Titan, haze production is expected from photochemistry of CH₄ in
404 Triton's atmosphere. Unlike Pluto, the colder temperatures and smaller mole
405 fraction of CH₄ in Triton's atmosphere means that the CH₄ is largely confined
406 to lower altitudes and does not reach the exobase (Strobel and Zhu, 2017).
407 Ethane (DeMeo et al., 2010; Holler et al., 2016) and HCN (Gurwell et al.,
408 2019) have tentatively been identified in earth-based spectra. In Triton's
409 cold atmosphere HCN and ethane grains could seed production of hydrocarbon
410 ice particulates (Lavvas et al., 2020; Ohno et al., 2020), forming the haze,
411 which would eventually precipitate onto the surface (Holler et al., 2016).
412 Alternatively the haze could be made up of submicron N₂ ice particulates
413 coming from seasonal sublimation and/or activity of plumes (Hillier &
414 Veverka, 1994).

415 Superficially, since the atmospheres of both Triton and Pluto are
416 predominantly composed of nitrogen with similar trace constituents one might
417 expect similar thermal structure, haze layers, etc. In fact the two are
418 quite different, and warrant further study (Strobel & Zhu, 2017).
419



420
421 *Figure 4. A discontinuous haze layer was imaged at Triton's limb by Voyager.*
422 *Based on PIA02203. Credit: NASA/JPL*

423
424 Winds are driven by gas released as polar ice sublimates, as evidenced
425 by the orientation of fan-shaped deposits on Triton's surface and the
426 orientation of Triton's plumes (Hansen et al. 1990; Ingersoll, 1990).
427 Geological evidence for winds may be revealed by the presence of dunes, like
428 those of Pluto, and if so stratigraphic relations and geologic context of
429 such aeolian landforms can further constrain relative ages of geologic events
430 and geologic processes (Telfer et al., 2018; Ferrell et al., 2020). For
431 example, dunes identified on Pluto are most prominent on the edges of glacial
432 nitrogen convection cells near the opening of mountain valleys (Ferrell et
433 al., 2020). These arrangements indicate youthful landforms (stratigraphically
434 atop another youthful unit) and implicate orographically-related winds for
435 their origins. Finding such evidence for such landforms and processes on
436 Triton requires imaging the surface at better than a few hundred meter
437 resolution.

438 *A future mission to Triton that maps the now illuminated north polar*
439 *region, surface ices, eolian landforms, and measures the density of the*

440 *atmosphere will illuminate Triton's complex climate history, yielding new*
441 *insights also applicable to Pluto and potentially other bodies in the Kuiper*
442 *Belt with atmospheres.*

443

444 **5. Triton's Plumes**

445

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

456 The plumes were initially hypothesized to be solar-powered eruptions:
457 driven by seasonal sublimation of nitrogen under translucent ice (i.e.,
458 solid-state greenhouse heating), pressurization, and explosive venting (Kirk
459 et al. 1995). This hypothesis was supported by the location of the plumes
460 near the subsolar latitude during the Voyager 2 encounter and the location of
461 the numerous dark streaks, presumably from former plumes, at latitudes
462 corresponding to the subsolar track in the decades prior to the Voyager 2
463 encounter. All plumes and fans were confined to the bright southern
464 hemisphere terrains, which were interpreted to be a cap of volatile ices,
465 adding further support to a volatile-based hypothesis (Hansen et al., 1990).
466 The model of solar-powered activity has challenges, however, including the
467 large size of the sub-ice nitrogen reservoir required (Kirk et al., 1995) and
468 the apparent absence of analogous plumes and fans on Pluto (Hofgartner et
469 al., 2018).

470 Brown and Kirk (1994) proposed an endogenic model where internal heat
471 melts the base of a thick nitrogen-ice polar cap and the plumes result from
472 exposure of the melt to the surface. A third hypothesis for Triton's plumes
473 is outgassing of its interior in the form of water-based cryovolcanism (Kirk
474 et al., 1995). For many years, the conventional wisdom favored the solar-
475 driven hypothesis; however, new datasets for the solar-driven jets of Mars
476 and the endogenic plume of Enceladus lead us to re-examine the solar-driven

477 hypothesis and ask whether the endogenic model might actually be the correct
 478 one (Hansen and Kirk, 2015).

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

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

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

505
 506 *Table 1. Comparison of Plume Properties*

Parameter	Mars	Triton	Enceladus
Volatile erupting	CO ₂	N ₂ or H ₂ O	H ₂ O
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

507 *Notes on Table 1. Values in the column for Mars are from Thomas et al.,*
508 *2011. Values for Triton are summarized in Kirk et al., 1995. Values for*
509 *Enceladus are from Goguen et al., 2013 (source vent diameter and*
510 *temperature), Hansen et al., 2020 (exit velocity and vapor mass flux),*
511 *Ingersoll & Ewald, 2011 (particle mass flux).*

512
513

514 **6. Triton's Unique Ionosphere and Interaction with Neptune's magnetosphere**

515

516 Voyager radio science observations revealed a significant ionosphere,
517 with a well-defined peak at ~350 km altitude and peak densities of 2-5 x 10⁴
518 cm⁻³ (Tyler et al. 1989). Due to Neptune's large distance from the Sun, such a
519 strong ionosphere was not anticipated from solar photoionization alone, and
520 it has therefore been suggested that precipitating electrons from Neptune's
521 magnetosphere are an important, and perhaps dominant, driver for Triton's
522 ionosphere (Krasnopolsky & Cruikshank, 1995; Majeed et al., 1990; Sittler &
523 Hartle, 1996; Strobel et al., 1990; Yung & Lyons, 1990). However, due to
524 Voyager 2's distant (~40,000 km) flyby of Triton, there were no in-situ
525 measurements made of Triton's local magnetospheric environment. Therefore,
526 the exact energy input from magnetospheric electrons to Triton's ionosphere
527 is poorly constrained, and it remains unconfirmed whether magnetospheric
528 electrons are indeed the dominant ionization agent in Triton's atmosphere.

529 Voyager 2 found that Neptune's magnetosphere contains heavy ions with
530 an inferred mass (10 - 40 Da, possibly N⁺) and average temperature (60 - 100
531 eV, consistent with pick-up at Triton's L-shell) that was consistent with a
532 Triton source, and Sandel et al. (1990) suggested that a source of 1 kg/s
533 from Triton's atmosphere could explain the observed power of the Neptunian
534 aurora. However, inconsistencies were later found between this inferred
535 source rate and multiple Voyager 2 datasets (Decker & Cheng, 1994; Richardson
536 et al., 1990). Thus, the exact role of Triton as a source of heavy ions to
537 Neptune's magnetosphere, and its role in generating Neptune's aurora, remains
538 unresolved.

539

540 *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 Ions: 0.0015 cm ⁻³	<i>Zhang et al., 1991</i> <i>Mauk et al., 1991</i> <i>Richardson et al., 1991</i>
Plasma Temperature	300 eV electrons 100 eV ions	<i>Sittler and Hartle, 1996</i>
Plasma Composition	50% N ⁺ / 50% H ⁺ <m> 7.5 amu	<i>Richardson and McNutt, 1990</i> <i>Mauk et al., 1991</i>
Relative Plasma Speed	43 km/s	<i>Sittler and Hartle, 1996</i>
Local Magnetic Field B 	5 - 11 nT	<i>Saur et al., 2010</i>
Alfven Speed	> 800 km/s	sub-Alfvénic & sub-magnetosonic
N⁺ Gyroradius at Triton	598 - 1315 km	Too large for MHD treatment

541 *Table 2: Bulk plasma and magnetic field environment local to Triton's orbit*
 542 *as observed by Voyager 2.*

543

544 Early modeling efforts suggested that Triton may have an Io (e.g.
 545 Strobel et al., 1990) or Venus-like (e.g. Sittler & Hartle, 1996) interaction
 546 with Neptune's corotating magnetospheric plasma. However, without detailed
 547 in-situ measurements at Triton, the nature of this interaction remains
 548 largely unknown. Voyager 2 observed the bulk plasma density, temperature and
 549 composition throughout its encounter with Neptune, and found the plasma at
 550 Triton's orbital distance to be quite diffuse, 0.003 particles/cm³, with
 551 temperatures of 100 eV, and composed of N⁺ and H⁺ in roughly equal parts
 552 (Sittler and Hartle, 1996). However, Triton was not close by when Voyager
 553 crossed at this orbital distance, and the plasma disk was crossed by the

554 spacecraft several Neptune radii away, leaving some uncertainty as to the
555 variability and full characterization of Triton's local environment. Table 2
556 summarizes the upstream environment near Triton's orbit observed by Voyager
557 2. Measurements of hot plasma and energetic charged particles by the Voyager
558 LECP instrument hinted to the fact that these populations appear to be
559 strongly affected by Triton and/or interactions with the hypothetical Triton
560 neutral torus, and that a distinct "trans-Triton" population of heavy
561 energetic ions exists outside the minimum L-shell of Triton (Mauk et al.,
562 1991).

563

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

568

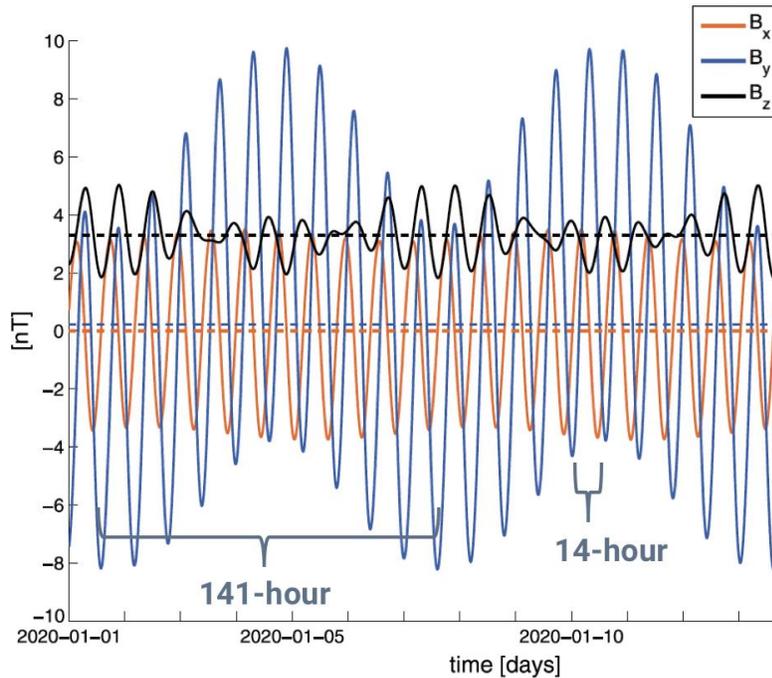
569 **7. How do we confirm that Triton is an Ocean World?**

570

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

577 Neptune's magnetic field can be represented by an off-centered dipole
578 that is tilted 46.8° relative to the planet's spin axis (Ness et al., 1989;
579 Connerney et al. 1991). Its 28.3° obliquity generates seasonal effects and,
580 combined with the magnetic geometry, generates a strong diurnal variability
581 of the magnetic field local to Triton with a 14-hour periodicity. Triton's
582 retrograde and highly inclined orbit (157°) also contributes a large
583 amplitude local magnetic field variation creating a second 141-hour period
584 wave. These magnetic waves and their harmonics in the rest frame of Triton
585 are shown in Figure 5, which was modified from Saur et al. (2010). An
586 internal ocean would produce an appreciable induced magnetic field (Saur et
587 al. 2010) at these harmonics that could be detected from orbit or by a well-
588 placed flyby (Nimmo and Pappalardo, 2016). Indeed, the abundance of solutes
589 (in particular carbonates) expected in the ocean can increase electrical
590 conductivity (EC) well above the EC resulting from the leaching of major
591 elements from the rock phase as a consequence of aqueous alteration (i.e., 1-

592 7 S/m vs. <1 S/m, e.g., Leitner and Lunine 2019; Castillo-Rogez et al. in
 593 prep.) This contrasts with the low (<1 S/m) electrical conductivities
 594 estimated at Europa and Callisto from the Galileo magnetometer (Zimmer et al.
 595 2000) and is explained by the lower abundances in carbon dioxide and ammonia
 596 accreted in these bodies, based on cosmochemical models (e.g., Kargel and
 597 Lunine 1998).



598
 599 *Figure 5. Neptune's magnetic field at the location of Triton varies strongly*
 600 *with time and possesses harmonics at both the synodic rotation period of*
 601 *Neptune and the orbital period of Triton. Such harmonics can be exploited for*
 602 *induction sounding of an ocean in Triton from a single or multiple flybys of*
 603 *Triton. Figure modified from Saur et al. (2010).*

604
 605
 606 Perhaps the most analogous ocean world detection to date has been that
 607 of Callisto orbiting Jupiter. Callisto is an icy ocean world, similar in size
 608 to Triton and in a similar plasma and magnetic field setting. Its ocean was
 609 detected using magnetic induction techniques from magnetic field measurements
 610 made by the Galileo spacecraft (Khurana et al., 1998; Kivelson et al., 1999;
 611 Zimmer et al., 2000). Callisto's environment is similar in that there is a
 612 dominant magnetic field oscillation due to Jupiter's dipole tilt, which
 613 causes a magnetic wave local to Callisto with an amplitude of ~ 40 nT (Saur
 614 et al., 2010). The Jovian plasma disk also oscillates up and down,

615 periodically sweeping over Callisto with enhanced plasma densities sourced
616 from the Io plasma torus. It was determined that plasma interaction fields at
617 Callisto would be too large to unambiguously detect an induction signal when
618 Callisto was located in the Jovian plasma disk (Liuzzo et al., 2015, 2018),
619 where the magnetic field is nearly orthogonal to the incident plasma flow of
620 192 km/s and the plasma density is relatively high (~ 0.15 particles/cm³). When
621 Callisto was located outside the plasma disk and in the magnetospheric lobe,
622 where plasma densities drop to between 0.04-0.06 particles/cm³, the plasma
623 interaction fields, which scale with square root of the plasma density
624 (Neubauer, 1980), were small and the induction signal was easier to identify.
625 At Triton, the local plasma density is much lower than that experienced by
626 Callisto, less than 0.003 particles/cm³ (Sittler and Hartle, 1996), and the
627 relative plasma speed is also significantly lower at 43 km/s. Plasma
628 interaction fields are thus not likely to contribute significantly to the
629 observed magnetic perturbation. The likelihood of detecting Triton's putative
630 ocean using magnetic induction is therefore high, due to two large amplitude
631 magnetic wave periods and a low density plasma environment.

632

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

645

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

650

651 **8. Where Triton fits in the Search for Life Elsewhere in the Solar System**

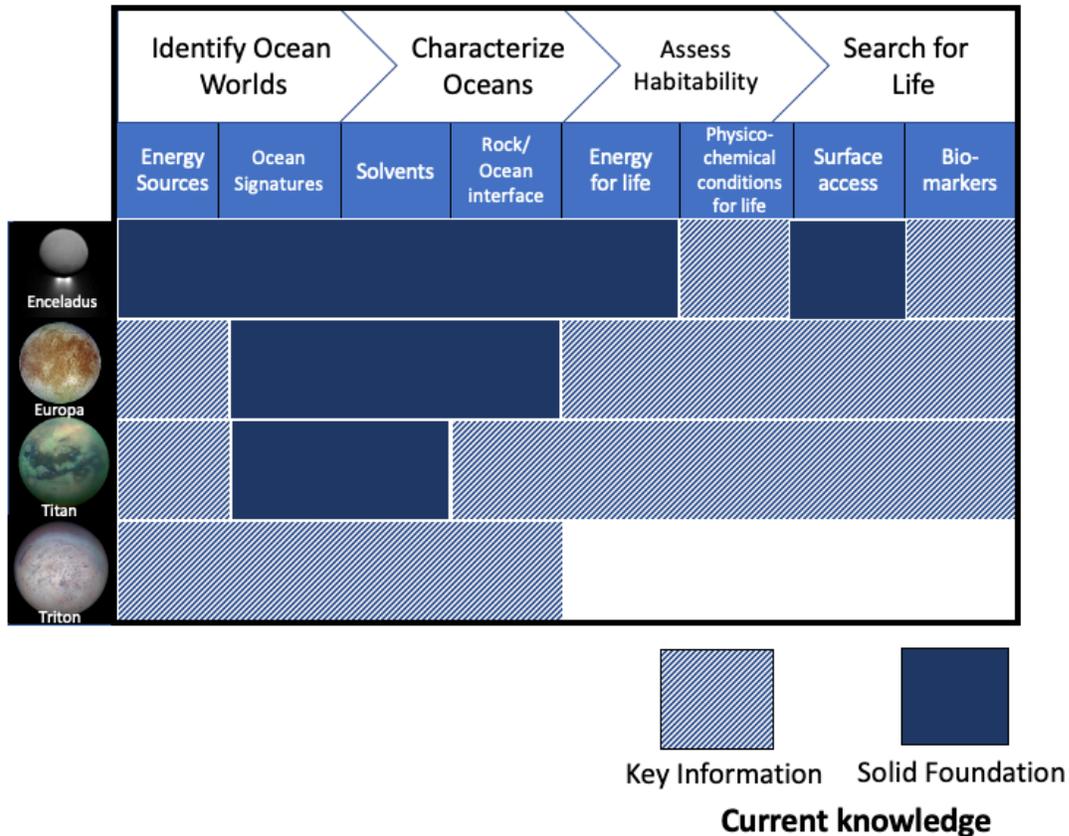
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653 Today we ask: is there life anywhere else in our Solar System besides
654 Earth? What conditions are required for life to appear and evolve? Do the
655 oceans of moons of other planets provide habitable environments? A
656 systematic sequence of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

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

668 Triton is a critical world as we seek to answer these questions - does
669 life exist everywhere in the Solar Systems' oceans? Or only in some oceans?
670 *To address these questions, and taking into account the long duration travel*
671 *time to Neptune, the groundwork must be laid now.* We must first ascertain
672 with certainty whether or not Triton is an ocean world. We must then
673 characterize the nature of its ocean and its accessibility - do cryovolcanic
674 terrains and/or active plumes include ocean material? Are there cracks or
675 faults or conduits with contact to the ocean reaching the surface? Is
676 organic material generated in the tenuous atmosphere reaching this potential
677 subsurface ocean?

678

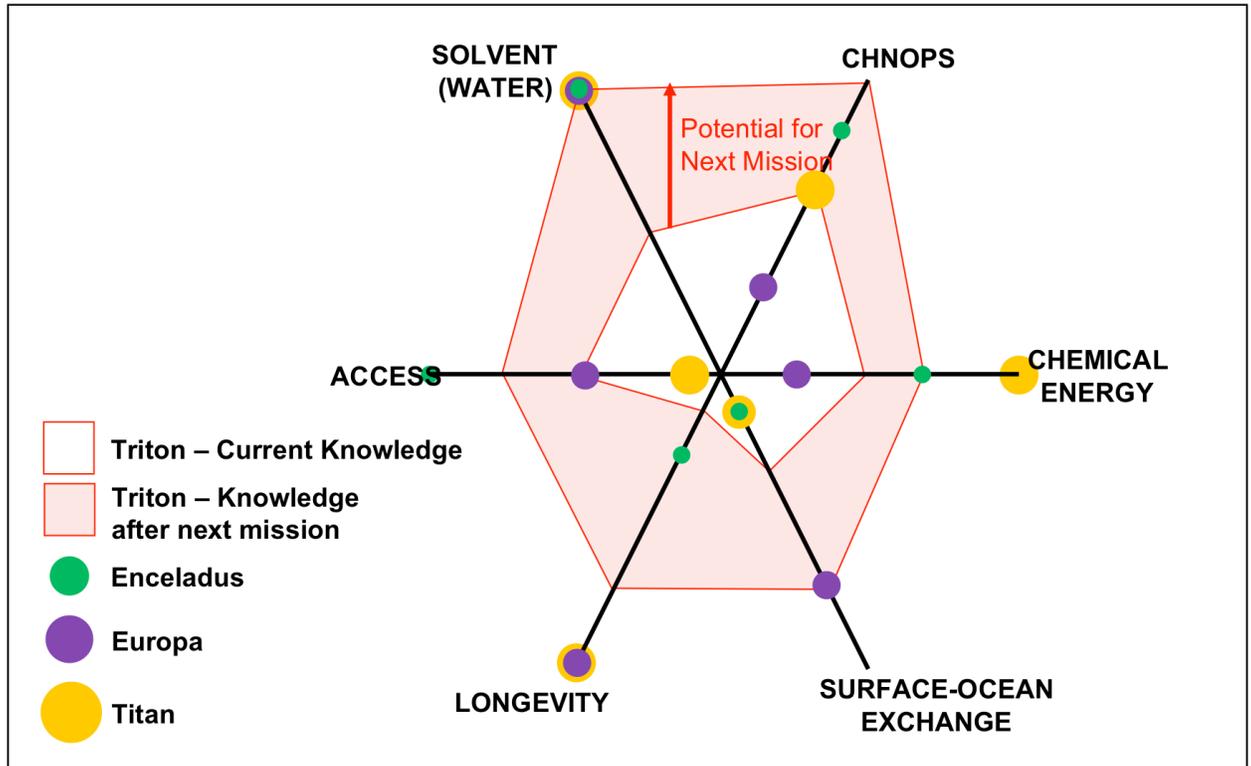


679
 680 *Figure 6. ROW outlined a systematic process for exploration of ocean worlds*
 681 *and the search for life that begins with the identification of ocean worlds,*
 682 *followed by characterization of the ocean and assessment of its habitability.*
 683

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

692 Figure 7 shows six key parameters related to the possibility of life,
 693 comparing Triton to Enceladus, Europa and Titan. The state of knowledge for
 694 each body is shown notionally; for example, all 4 are known to have water;
 695 however access of material from a subsurface ocean to the surface ranges from
 696 completely certain at Enceladus to very uncertain at Titan. Both Triton and
 697 Titan are known to have C, H, O and N, but ascertaining the presence of P and

698 S awaits the next mission(s). The oceans of Titan and Europa are
 699 substantial and long-lived, but Enceladus' ocean may not be. Chemical energy
 700 refers to the production of organics - known with certainty for Titan's haze,
 701 likely present in Enceladus' plume (large molecules are detected but
 702 identification of which species is ambiguous), and expected from
 703 serpentinization at Europa.
 704
 705



706
 707 *Figure 7. This is a notional comparison of Triton to other known ocean*
 708 *worlds in terms of key parameters defining a body's habitability potential.*
 709 *"Access" refers to one-way transfer of material from the ocean to the*
 710 *surface; "Exchange" refers to one-way transfer of material from the surface*
 711 *to the ocean. In the case of Triton, the state of knowledge is assessed from*
 712 *observations returned by Voyager 2 and geophysical modeling (see text for*
 713 *additional detail). Future knowledge of Triton is a hypothetical best case*
 714 *for a Triton flyby or Neptune-system mission.*

715
 716 Icy moons and dwarf planets may have begun as ocean worlds, and we
 717 suspect that some still are (see Hendrix et al. 2019 for review). With 150
 718 large icy bodies (130 heliocentric plus 19 moons) with diameter > 400 km, the
 719 field is ripe for investigating their window for habitability. Hence, the

720 future exploration of Triton would not only explore the boundaries of
721 habitability in our Solar System, with application to other solar systems,
722 but also test the modalities of fundamental processes that determine the
723 habitability potential of icy bodies.

724

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

728

729 **9. Future Missions to Triton (and Neptune)**

730

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

747

748 A Flagship mission in orbit around Neptune, such as the recent Neptune
749 Odyssey planetary mission concept study [Rymer et al., 2020a,b], would yield
750 Cassini-level scientific return on the entire ice giant system as well as
751 both broader and more in-depth investigations of Triton itself. An orbiter
752 with a robust modern payload performing multiple Triton flybys offers the
753 opportunity to do *comprehensive* photogeologic and spectral mapping of
754 Triton's surface and volatile distribution, probe the deep interior of Triton
755 from electromagnetic sounding and geodesy, and to study time domain
756 variability of Triton's atmosphere, magnetosphere, and surface. It could
757 also adapt to new discoveries to further investigate Triton, just as, for
example, Cassini did at Enceladus and Titan. Compiling observations from

758 multiple flybys of Triton also enables comprehensive characterization (e.g.,
759 salinity and thickness) of the likely subsurface ocean, necessary for
760 ascertaining habitability. A Neptune system orbiter could answer Triton
761 science questions, and is the key to unlocking our understanding of both ice
762 giants and to making the next major advance in Kuiper Belt dwarf planet
763 science.

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

775
776 The final argument for a mission to Triton comes from the broader
777 community, in the form of the OPAG **Roadmap to Ocean Worlds (ROW)**
778 **recommendation:** Among the candidate ocean worlds in the Solar System "*Triton*
779 *is deemed the highest priority target to address as part of an Ocean Worlds*
780 *Program. This priority is given based on the extraordinary hints of activity*
781 *shown by the Voyager spacecraft (e.g., plume activity; smooth, walled plains*
782 *units; the cantaloupe terrain suggestive of convection) and the potential for*
783 *ocean-driven activity given by Cassini results at Enceladus. Although the*
784 *source of energy for Triton's activity remains unclear, all active bodies in*
785 *the Solar System are driven by endogenic heat sources, and Triton's activity*
786 *coupled with the young surface age makes investigation of an endogenic source*
787 *important."* (Hendrix and Hurford, 2019).

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

790

791

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798
799
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