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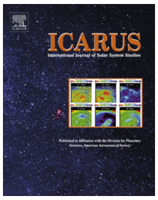

Powering Triton's recent geological activity by obliquity tides: Implications for Pluto geology

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ABSTRACT

We investigate the origins of Triton's deformed and young surface. Assuming Triton was captured early in Solar System history, the bulk of the energy released during capture will have been lost, and cannot be responsible for its present-day activity. Radiogenic heating is sufficient to maintain a long-lived ocean beneath a conductive ice shell, but insufficient to cause convective deformation and yielding at the surface. However, Triton's high inclination likely causes a significant ($\approx 0.7^\circ$) obliquity, resulting in large heat fluxes due to tidal dissipation in any subsurface ocean. For a 300 km thick ice shell, the estimated ocean heat production rate ($\approx$0.3 TW) is capable of producing surface yielding and mobile-lid convection. Requiring convection places an upper bound on the ice shell viscosity, while the requirement for yielding imposes a lower bound. Both bounds can be satisfied with an ocean temperature $\approx$240 K for our nominal temperature-viscosity relationship, suggesting the presence of an antifreeze such as NH_3. In our view, Triton's geological activity is driven by obliquity tides, which arise because of its inclination. In contrast, Pluto is unlikely to be experiencing significant tidal heating. While Pluto may have experienced ancient tectonic deformation, we do not anticipate seeing the kind of young, deformed surfaces seen at Triton.

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1. Introduction

In terms of their bulk properties, Triton and Pluto are remarkably similar (see Table 1). Both are presumed to have formed as Kuiper Belt objects, although retrograde Triton was captured into Neptune orbit at some point in its history (McKinnon and Kirk, 2007). Triton has a young (<100 Myr) surface (Schenk and Zahnle, 2007), deformed by a variety of tectonic and possibly cryovolcanic (Croft et al., 1995) features, and exhibits geysers that are probably powered by solar heating (Kirk et al., 1990). It is therefore of interest to consider the question: to what extent will Pluto resemble Triton?

In this MS we lean heavily on Triton's youthful appearance in assessing its likely interior state. With Pluto, firm predictions are elusive. However, we argue that *New Horizons* observations will not only clarify Pluto's interior state, but will also determine whether our favoured hypothesis for Triton's activity is correct.

The logic of the MS is as follows. We first demonstrate that the heat released during Triton's orbital evolution following capture only marginally affects its present-day behavior (Section 3.1). Based on its young apparent age, we assume that Triton's icy surface is being deformed, at least in part, by convection (c.f. Stern and McKinnon, 2000), as similarly young surfaces on Europa and Enceladus are thought to do. We then argue that surface deformation and yielding require heat fluxes much greater than Triton's radiogenic elements can supply (Section 3.2). However, the addition of tidal heating is sufficient to permit yielding to occur, and also makes a long-lived ocean possible. As argued by Jankowski et al. (1989), Triton's odd orbital configuration makes heating by obliquity tides unusually effective. In contrast to these authors, however, we focus on dissipation within a subsurface ocean (Section 3.3). A Triton consisting of a thick convecting ice shell overlying a long-lived, cold (and currently dissipative) ocean is energetically plausible and consistent with the meagre observational constraints.

How does this picture relate to Pluto? The main difference is that tidal heating is unlikely to operate at Pluto and, as a result, surface yielding should not be occurring currently. If our scenario regarding Triton's extra energy source is correct, Pluto should show no signs of recent geological activity. Conversely, if Pluto's surface does turn out to be as young as Triton's, this suggests that processes other than tidal heating are likely responsible for the activity of both moons. One possible explanation in this case would be the presence of highly volatile species enabling geological activity powered by radiogenic heat alone.

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Table 1
Parameter values for Triton and Pluto. "Eqn." = equation, "Qty." = quantity. For Pluto, orbital parameters (P, e, m_p, i, a) are for the relevant tide-raising body (Charon).

Qty.	Triton	Pluto	Units	Eqn.	Qty.	Triton	Pluto	Units	Eqn.
R	1353	1153	km	(1)	ρ_b	2061	2030	kg m^{-3}	(1)
R_s	1026	866	km	(1)	d_{max}	327	287	km	–
g	0.779	0.658	m s^{-2}	(4)	P	5.877	6.387	days	–
e	0.000016	<0.000075[a]	–	(8)	i	156.87°	0[b]	–	(9)
T_s	38	44	K	(4)	a	355,000	19,573	km	(2)
R_p	25,300	–	km	–	m_p	1.02×10^{26}	1.52×10^{21}	kg	(2)

[a] Upper limit from Buie et al. (2012).

[b] Inclination of Charon relative to Pluto rotation axis. This has not been measured but is expected to be very small due to tidal damping.

Because of the relative paucity of observational constraints compared to e.g. the saturnian or Jovian satellites, we have favoured order-of-magnitude arguments over detailed models wherever possible. Uncertainties are generally so large that exploring parameter space with complex models is impractical, and unlikely to yield additional insight beyond the simple calculations presented here. We do, however, identify some questions which may be worth exploring in more detail.

1.1. Observations

An important clue to Triton's present-day state is the fact that its surface is so lightly cratered, suggesting a surface age less than at most 100 Myr old (Schenk and Zahnle, 2007). There are only four other known outer Solar System bodies with comparable surface ages. Titan and Io are unsuitable analogues, because the resurfacing is due in large part to erosion/sedimentation, and prodigious silicate volcanism, respectively. Europa's heavily deformed surface is about 50 Myr old on average (Zahnle et al., 2003), while the south polar region of Enceladus is probably even younger (Porco et al., 2006). In both cases, resurfacing is plausibly due to deformation driven by convection involving motion of the entire near-surface lid (Showman and Han, 2005; Barr, 2008; O'Neill and Nimmo, 2010). In both cases the ultimate energy source driving this motion is tidal heating. Given the abundance of plausibly tectonic features on Triton's surface (Croft et al., 1995), we shall assume below that convection-related yielding and deformation is taking place. We note, however, the possibility that mechanisms other than ice shell convection, such as cryovolcanism (Croft et al., 1995) or diapirism driven by local density variations (Schenk and Jackson, 1993) may also contribute to Triton's resurfacing.

While Triton is also active up to the present time in the sense that it has active geysers, we do not view this as a particularly useful constraint. Although the geysers at Enceladus are probably related to its internally active state, Triton's geyser activity is plausibly driven by solar heating (Kirk et al., 1990) rather than endogenic geological activity.

1.2. Orbital history

Triton's retograde orbit indicates that it was captured. Three capture mechanisms have been proposed: aerodynamic drag (McKinnon and Leith, 1995); collision with another satellite (Goldreich et al., 1989); and exchange capture (Agnor and Hamilton, 2006). Of these, the last – in which a binary object encounters Neptune and one member of the binary (Triton) is captured – is by far the most probable. The timing of the capture event is somewhat unclear. Aerodynamic drag can only have operated during Neptune's formation, and the probability of a collision, always low, becomes much lower once the main stage of accretion ended. Exchange capture could in theory occur at any time, but modeling by Vokrouhlicky et al. (2008) suggests that it probably happened within the first 5–10 Myr of Solar System history.

The conventional picture of Triton's post-capture orbital evolution may be divided into two phases (Chyba et al., 1989; Ross and Schubert, 1990). In the first phase, its initially highly eccentric orbit was circularized by tidally-driven dissipation. Because of the strong positive feedback between dissipation and temperature, the majority of the circularization probably took place rapidly (<100 My). The duration of the entire circularization process depends on poorly-known rheological parameters, but was almost certainly <1000 Myr. An alternative, more rapid (~0.1 My) mode of circularization is via interaction with a disk resulting from collisions between other pre-existing satellites (Cuk and Gladman, 2005). In either case, the end state was a body on an inclined, but essentially circular orbit.

The second phase involves more gradual evolution to the present-day situation. Tidal dissipation in a satellite damps both eccentricity and inclination, while dissipation in the primary can have the opposite effect (Murray and Dermott, 1999). For the Neptune–Triton system, it is not obvious whether dissipation in the primary or the satellite dominates (Chyba et al., 1989). However, irrespective of this issue, the inclination will damp more slowly than the eccentricity (as is evident from the current circularity of Triton's orbit). We discuss this issue in more detail in Section 3.3 and Eq. (9) below, and demonstrate that the inclination is not expected to have damped over the age of the Solar System. The reason this issue is important is that it is Triton's non-zero inclination which we hypothesize is the ultimate cause of present-day tidal heating (Section 3.3).

2. Structure and parameter choices

For a body consisting of two layers of uniform density, the bulk density ρ_b is given by

$$\rho_b = \rho_i \left(1 + \frac{(\rho_s - \rho_i)}{\rho_i} \left[\frac{R_s}{R} \right]^3 \right) \tag{1}$$

where the density of the outer and inner layers are ρ_i and ρ_s, respectively, and the radial position of the interface is R_s. For Triton and Pluto, we assume the outer layer is Ice I ($\rho_i = 950$ kg m^{-3}) and the inner layer is anhydrous silicates plus iron with a density similar to Io's ($\rho_s = 3500$ kg m^{-3}). The resulting radius of the rock–iron core R_s and the maximum thickness of the ice shell d_{max} are given in Table 1. Triton's maximum ice shell thickness is 327 km; a lower density inner layer results in a thinner shell (e.g. 284 km for $\rho_s = 3200$ kg m^{-3}). The actual shell thickness may also be smaller if a subsurface ocean is present.

This simple analysis ignores many details: the role of higher pressure ice phases, the possibility of a hydrated core, porosity in the near-surface of the ice shell, and so on. However, at the order-of-magnitude level that we are discussing, none of these details are likely to matter. One important exception is that Pluto (but not Triton) might not be fully differentiated. We discuss this issue briefly in Section 5.

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