**INTENSE GEOLOGIC ACTIVITY ON TRITON FOR BILLIONS OF YEARS AFTER ORBITAL CAPTURE.** N. P. Hammond[1], G. Collins[2] [1]College of the Holy Cross, Biology Department, Worcester MA, nhammond@holycross.edu, [2]Wheaton College of Massachusetts, Department of Physics and Astronomy, Norton MA.

**Summary:** After being captured into Neptune's orbit, Triton was likely intensely tidally heated and melted as its highly eccentric orbit was gradually circularized. However, as melting caused the ice shell to thin, the magnitude of tidal dissipation decreased as the volume of the dissipating region grew smaller. Reduced dissipation rates in turn slowed down the rate of tidal decay and orbit circularization.

We use a coupled thermal-orbital evolution model to explore Triton's internal evolution after capture. We find that Triton's eccentricity may have decayed over 1 to 3 billion years, much longer than previous estimates. We also find that Triton's ice shell during this time would have been extremely thin, only 2 – 5 km thick. Tidal stresses would have been strong enough to fracture the entire ice shell down to the subsurface ocean, perhaps generating Enceladus-like geysers or even a Titan-like atmosphere. Such a prolonged period of activity could help explain Triton's geologically young surface and have major implications for Triton's habitability.

**Background:** Triton, Neptune's largest satellite, is an incredibly strange and fantastic world. Its surface is covered in the geologically young cantaloupe terrain [1], and Voyager-2 images spotted active geysers erupting from the surface [2], possibly driven by solar heating of nitrogen ice [3]. Triton is also on a retrograde orbit, and Neptune has very few large regular satellites, suggesting Triton may be a captured Kuiper Belt object [4,5]. Several mechanisms could explain how Triton was captured into Neptune's orbit, including gas-drag with Neptune's atmosphere, and collisions and angular momentum exchange between Triton and pre-existing satellites [6,7]. The most statistically likely mechanism may be that Triton was part of a binary system (similar to Pluto-Charon) and that during capture, Triton's binary partner was scattered, leaving Triton behind [8].

After capture, Triton's initial orbit would have been highly eccentric, causing Triton to experience intense tidal deformation and heating. Several studies have found that Triton's eccentricity likely decayed to its current-day, nearly circular orbit in less than 1 billion years [9,10,11], and the total energy generated by tidal heating would have been enough to melt all of Triton's ice several times over [11].

But approximately how thin would Triton's ice shell have been during this period? Tidal dissipation is thought to predominantly occur in the solid ice shell, and as the ice shell gets progressively thinner, the reduced ice shell volume causes the energy dissipation rate on Triton to decrease. Thus, an equilibrium ice shell thickness will develop, where tidal energy dissipation is balanced by heat loss to the surface. This equilibrium dissipation rate will control the eccentricity decay rate.

**Model:** We use a coupled thermal and tidal evolution model to examine how Triton's ice shell evolves after capture into a highly eccentric orbit. The model calculates the temperature evolution of the ice shell and ocean formation rate, accounting for tidal dissipation, radiogenic heating from the core, latent heat, and conductive or convective heat transport in the ice shell [12]. The ice melting temperature varies with depth and the composition of the ocean, where we vary the ammonia concentration from 0 to 10% [13,14]. We use a composite rheology to calculate the viscosity of the ice shell [15]. The complex love number $\tilde{k}_2$, which controls the magnitude of tidal dissipation, is calculated through time as ocean thickness and temperature and viscosity structure of the ice shell changes assuming Maxwell dissipation [16].

The semi-major axis and orbital eccentricity evolve according to [10,11]:

$$\frac{da}{dt} = \frac{-21}{64}\frac{\omega}{\mu}\frac{a^2 R_T^5}{r_p^6}\tilde{k}_2, \qquad e > 0.145$$

$$\frac{de}{dt} = \frac{-21}{2}\frac{\omega e}{\mu}\frac{R_T^5}{a^5}\tilde{k}_2, \qquad e < 0.145$$

where $\omega$ is the orbital frequency, $\mu$ is the Triton/Neptune mass ratio, $R_T$ is Triton's radius and $r_p$ is Triton's pericenter distance. Semi-major axis and eccentricity coevolve such that angular momentum is conserved. We only calculate degree-2 tides (even though higher degree tides may be important at large eccentricities) and we assume that Triton quickly becomes tidally locked. We include obliquity tidal dissipation in the ocean [17] using an obliquity of 0.7° [18]. We explore a variety of initial orbital conditions and ice shell properties to understand how these influence Triton's orbital/thermal evolution.

***Table 1:*** *Initial conditions and internal properties.*

| | | |
|---|---|---|
| Initial Semi-major axis | $a_0$ | 20 – 1000 $R_N$ |
| Initial Eccentricity | $e$ | 0.53 – 0.98 |
| Initial Core Temperature | $T_{c,0}$ | 200 – 260 K |
| Ice Grain Size | $d$ | 0.1 – 10 mm |
| Ammonia Conc. | $C_{NH3}$ | 0 – 10 % |

**Results:** Our results show that Triton's orbit evolves slowly until an ocean is generated. Once an ocean forms, increased dissipation leads to rapid melting over a period of $10^5$ to $10^7$ years. The ice shell then reaches a minimum thickness of 2 – 5 km.

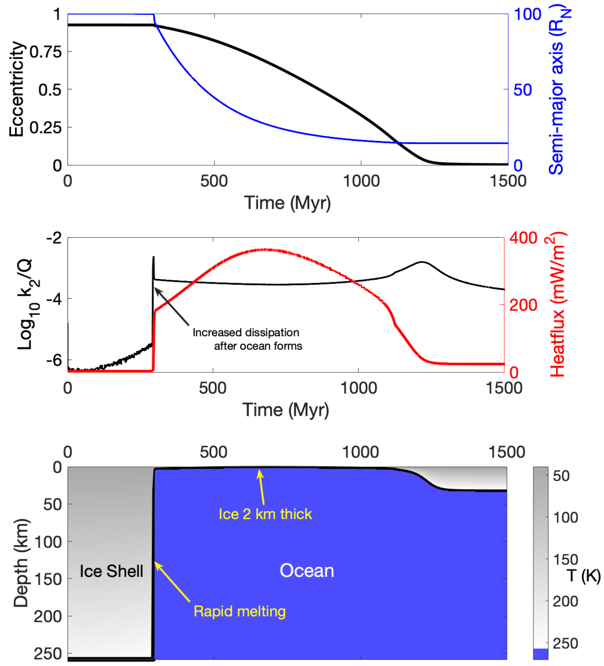


***Figure 1:*** *Simulation of Triton's orbital evolution for $a_0 = 100$ $R_N$, $d = 5$ mm, $T_{c,0} = 240$ K, $C_{NH3} = 0$. Top panel shows semi-major axis and eccentricity, middle panel shows complex $k_2$ and surface heat flux, bottom panel shows ice shell temperature with depth and ocean thickness.*

**Results (Continued):** The thin ice shell reduces the rate of tidal dissipation and orbital decay, and the eccentricity decays over a period of 500 Myr to 2 Byr. Figure 1 shows one such example where Triton has a thin ice shell for approximate 1 Byr before eccentricity decays and the ice shell thickens to ~30 km.

For certain initial conditions, such as an initial semi-major axis 1000 Neptune radii *($R_N$)* and an ice grain size of 0.5 mm, eccentricity decays over a period of ~3 billion years. Figure 2 shows a suite of simulations with different starting semi-major axes and ice grain sizes. Orbital decay times range from 500 Myr to over 3 Byr. Only two simulations, both with a grain size of 0.2 mm, failed to evolve in the age of the solar system.

**Discussion:** Due to the negative feedback between ice thickness and dissipation rates, we find that Triton's eccentricity decays over longer period than previously thought [9,10,11]. It is possible that processes other than viscous deformation in the ice could dissipate tidal energy and increase orbital evolution rates. We find, however, that dissipation of eccentricity tides in the ocean is negligible when the ocean is thick [19]. Preserving Neptune's irregular satellites may require Triton's semi-major axis to quickly decay within 100 $R_N$ [6], but long tidal evolution times are still possible under this condition.

Triton would have experienced intense geologic resurfacing during this prolonged period of tidal evolution. Large tidal stress (>100 kPa at the base of the ice shell and much larger at the surface) would have been capable of opening fractures through the ice shell to the ocean, generating Enceladus like geysers. Additionally, volatiles such as nitrogen, methane and carbon monoxide would have been vaporized from the subsurface, potentially generating a significant atmosphere that later collapsed as Triton cooled [20]. This extended period of orbital decay and geologic activity can explain why Triton's surface appears to be so young.

Exploration of Triton by future spacecraft, such as Trident, could help uncover the secret history of this incredible world [21]. We plan to continue updating our model in order to make testable predictions for Triton's ice thickness, orbital properties and thermal history.

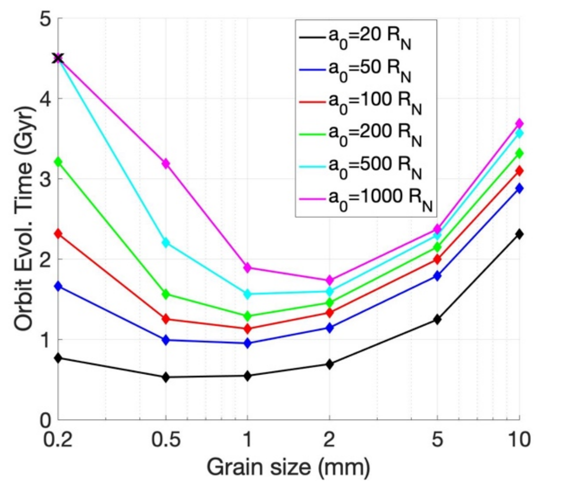


***Figure 2:*** *Orbital evolution (eccentricity decay) time plotted for 36 different simulations with different starting semi-major axes and ice grain sizes. X symbols show simulations that did not fully evolve in 4.5 billion years.*

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