A MODERN DYNAMO AS A CONSEQUENCE OF TRITON'S CAPTURE AT NEPTUNE.

L. J. Tilke[1], K. T. Trinh[1,2], and J. G. O'Rourke[1]. [1]School of Earth and Space Exploration, Arizona State University, PO Box 876004, Tempe, AZ 85287, [2]Division of Geological and Planetary Sciences, California Institute of Technology, 1200 East California Boulevard, Pasadena, CA 91125 (ltilke@asu.edu, ktt@caltech.edu, jgorourk@asu.edu).

Introduction: Triton, Neptune's largest moon, is considered one of the highest-priority candidate ocean worlds to explore [1]. Much of the icy moon remains shrouded in mystery; it has been visited once, in a 1989 *Voyager 2* flyby that imaged a mere ~40% of its surface. The spacecraft observed geyser-like plumes [2] and a young surface age [3, 4], but did not carry a magnetometer, a critical instrument for detecting subsurface oceans in icy bodies. Future missions may confirm the presence of a subsurface ocean if Triton has a time-variable induced magnetic field, best explained by the existence of an electrically conductive layer (i.e., salty ocean) beneath Triton's surface.

Triton's orbit is quite unusual: near-circular, highly inclined, and retrograde, indicating it may not have formed in orbit of Neptune and may instead be a captured Kuiper Belt Object [5]. Consequently, Triton's orbital evolution may provide a large source of energy to drive interesting phenomena.

Ganymede, the largest moon in the Solar System, is also the only moon with a known, ongoing dynamo. This dynamo produces a magnetic field originating from within a planetary body, powered by the vigorous convection of an electrically conductive fluid, like in Earth's metallic core. Pluto is perhaps the closest known analogue to Triton in the Solar System, but there is no evidence that it possesses a metallic core or active dynamo [6]. In contrast, the immense heating Triton experienced during its capture by Neptune, and subsequent orbital circularization, may have fully differentiated its interior and spawned a convecting, metallic core.

Essentially, Triton's capture by Neptune means that the moon may be more likely to host a dynamo than other icy satellites with similar (or larger) sizes.

Methods: We parameterized the thermal and magnetic evolution of Triton's hypothesized silicate mantle and metallic core, beginning immediately after differentiation and mantle solidification and continuing until our models predict that the dynamo would die.

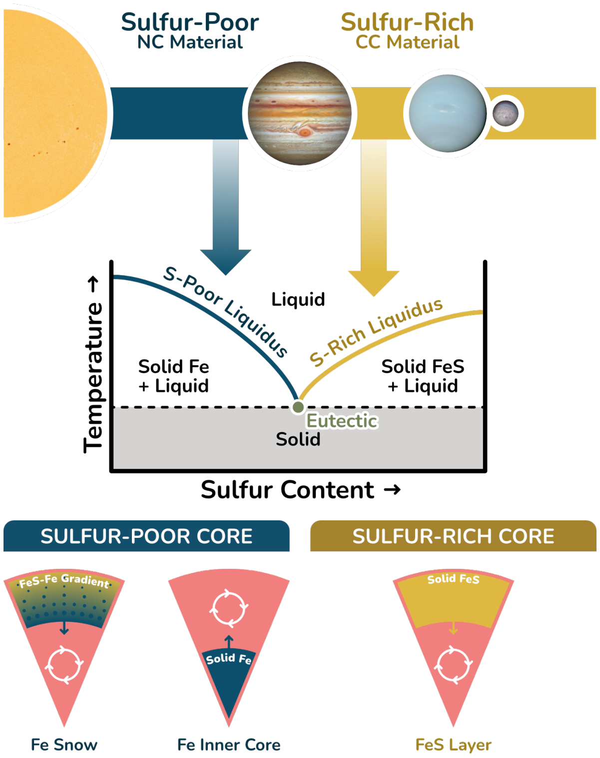


Figure 1. Triton's formation location likely correlates the sulfur content and composition of its interior, which in turn affects the size and crystallization mode of the core. We consider the sulfur-rich, "FeS Layer" model our nominal [12].

Internal Heating Sources. Before the start of our models, Triton primarily underwent three sources of heating: accretion, orbital circularization, and core formation. The most dramatic of the three, and what distinguishes Triton the most from other small, icy planetary bodies, is a direct result of its capture by Neptune. Regardless of the specific dynamics of capture, Triton's orbit (relative to Neptune) circularized from an eccentricity of ~1 to nearly 0. We can represent the maximum heat from this dynamical interaction as an equivalent change in the mean temperature of Triton:

$$\Delta T_{circ} = \frac{GM_N}{2aC_P} \approx 10{,}000\text{ K},$$

where M_N is the mass of Neptune, a is the semi-major axis of Triton, and C_P is the bulk heat capacity of Triton. However, the actual temperature increase could have been (much) smaller depending on the timescale of the orbital evolution. In any case, this immense heating plausibly resulted in widespread melting, differentiating the moon's interior into a metallic core, silicate mantle, and liquid ocean underneath its ice shell [7]. As Triton cools, the core will cool and, eventually, crystallize.

Core Crystallization Regimes. We model three modes of core crystallization: iron snow (Fe Snow), Earth-like inner core growth (Fe Inner Core), and iron sulfide layer solidification (FeS Layer). Geochemical

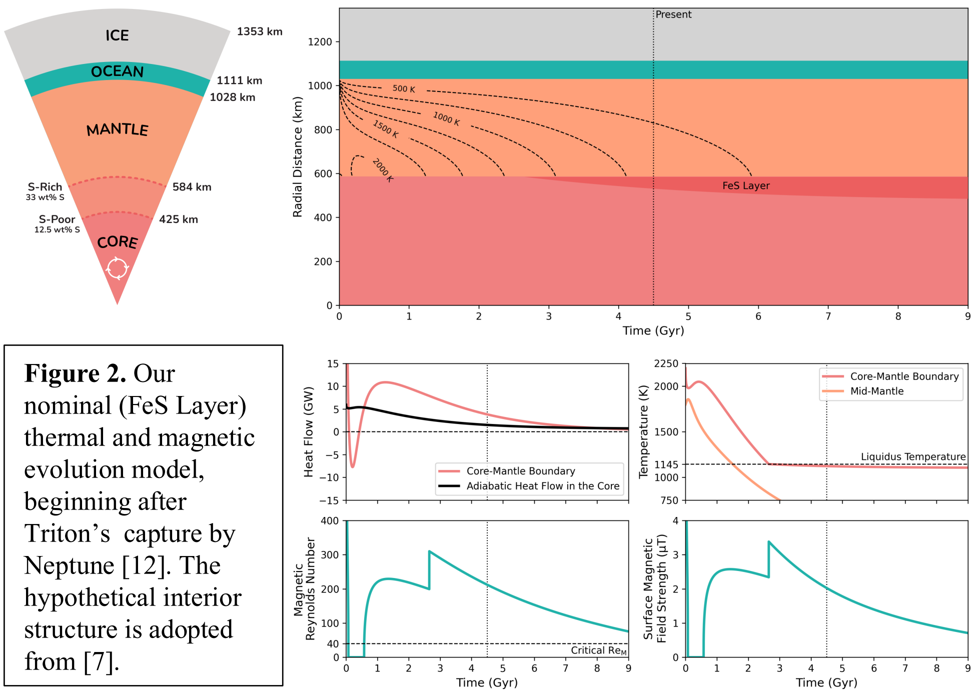


Figure 2. Our nominal (FeS Layer) thermal and magnetic evolution model, beginning after Triton's capture by Neptune [12]. The hypothetical interior structure is adopted from [7].

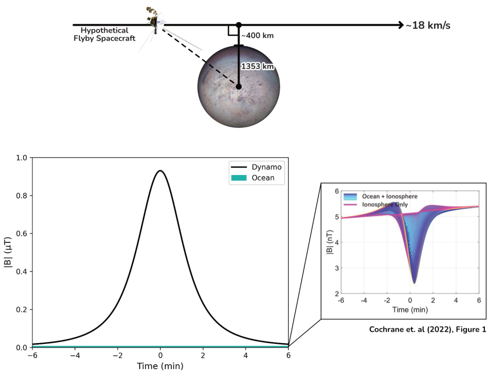
modelling indicates that the heating of carbonaceous chondrite (CC)-like material may lead to relatively sulfur-rich cores, whilst non-carbonaceous (NC)-like material results in sulfur-poor cores [8]. FeS layer solidification is our nominal model, presuming Triton formed in the outer solar system from CC-like material after Jupiter's partitioning of the protoplanetary disk.

Dynamo Theory. A dynamo may be quantified via the (nondimensional) magnetic Reynolds number (Re_M); a higher Re_M correlates to a higher magnetic field strength. Re_M primarily depends on the typical flow velocity of the convecting, conductive fluid, which in turn is proportional to the buoyancy flux of the system [9]. Initially, the total buoyancy flux is purely thermal, with the sinking of colder fluid and rising of hotter fluid driving convection. Once core crystallization begins, chemical buoyancy flux is released in addition.

FeS Layer Solidification. If Triton's core has a supereutectic sulfur content, we expect FeS to crystallize near the top of the core. The relatively Fe-rich residual fluid is less buoyant and will sink, strengthening the vigorous convection of the core and intensifying a dynamo [10].

Results: Our nominal model predicts that Triton's core may be able to sustain a dynamo for greater than 9 Gyr, with a present-day strength on the order of ~1 μT.

Figure 3. The predicted strength of a dynamo field compared to an ocean-induced magnetic field during a hypothetical flyby [12, 11].



Cochrane et. al (2022), Figure 1

A sensitivity analysis of several primary model parameters (initial core and mantle temperatures, core sulfur content and thermal conductivity, and radiogenic heating rate) demonstrates that in nearly all cases, Triton can sustain a dynamo for well over a billion years.

Conclusion: A future mission to Triton will likely be equipped with a magnetometer to search for a putative subsurface ocean. If Triton possesses a dynamo at present day, a single flyby (e.g. [11]) would be unable to discern the comparably miniscule, induced field of an ocean. Regardless, confirming the presence (or lack thereof) of an active dynamo will elucidate Triton's composition, structure, formation history, and subsequent evolution. An orbiter mission may be required to assess the prospect of both a salty ocean and dynamo at Triton.

References: [1] Hendrix, A. R. et al. (2019) *Astrobiology*, *19,* 1-27. [2] Soderblom, L. A. et al. (1990) *Science, 250,* 410-415. [3] Schenk, P. M. and Zahnle, K. (2007) *Icarus, 192,* 135-149. [4] Stern, S. A. and McKinnon, W. B. (2000) *AJ, 119,* 945-952. [5] McKinnon, W. B. (1984) *Nature, 311,* 355-358. [6] McComas, D. J. et al. (2016) *JGR: Space Physics, 121,* 4232-4246. [7] Nimmo, F. et al. (2025) In *Triton and Pluto*, 2.1-2.31, IOP Publishing. [8] Trinh, K. T. et al. (2024) *GRL, 51,* e2024GL110680. [9] Olson, P. and Christensen, U. R. (2006) *EPSL, 250,* 561-571. [10] Rückriemen, T. et al. (2018) *Icarus, 307,* 172-196. [11] Cochrane, C. J. et al. (2022) *ESS, 9,* e2021EA002034. [12] Tilke et al. (in revision).