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Triton's Path to Circularisation: Implications of Frequency-Dependent Tidal Dissipation and Ice Shell Feedback

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Neptune's moon Triton is most likely a captured Kuiper-belt object [1, 2]. After capture, Triton was deposited onto a highly eccentric and energetic orbit from which it circularised to its present day nearly circular orbit [3]. Triton's circularisation was driven by tidal dissipation, which transformed orbital energy into heat. Where and when this energy was deposited in Triton's interior will have large consequences for its interior evolution and putative subsurface ocean.

The timescales estimated for this process vary wildly between past studies (ranging from ~10 Myr [4], 300-1500 Myr [1, 5-7] to ~3.5 Gyr [8]), and the corresponding predictions on interior evolution vary between large-scale melting of Triton's silicate interior [6] to a silicate mantle that is hardly affected by tides [8]. This discrepancy arises from the use of various simplifying assumptions not necessarily appropriate at the high eccentricities Triton experienced (e.g. [9]): neglecting the tidal deformation due to higher-order tidal Fourier modes in the Darwin-Kaula expansion greater than O(e^2) [5, 10], assuming no or a linear frequency-dependence of the tidal response [7, 8], or imposing synchronous rotation on the moon [5, 8, 10]. In this work, we relax these assumptions and revisit Triton's interior-orbital evolution.

To do so, we couple a high-fidelity dynamical evolution model based on the expressions of [11] to a 1D interior-evolution model of Triton. The thermal and orbital evolution models are coupled via the tidal response, given by the Love numbers. We compute the frequency-dependent Love numbers using the thin-shell theory of [12] and a Maxwell rheology. We simulate the thermal-orbital evolution of Triton over 5 Gyr after capture at an initial eccentricity of e=0.97, and compare our results against those predicted by dynamical models used in previous work.

We find that the assumptions made in previous work are largely not justified, and misestimate Triton's evolution. Premature truncation of the Darwin-Kaula expansion leads to significant underestimation of tidal dissipation and consequently to significant overestimation of circularisation timescales; uncoupled models, in contrast, predict longer circularisation timescales. As opposed to what it is often assumed, Triton does not spend most of its evolution in synchronous rotation, instead cascading through a series of higher-order spin-orbit resonances until reaching lower eccentricities (~0.2).

In our simulations, Triton dissipates the vast majority of its orbital energy in its ice shell, resulting in the shell receding to thicknesses of 10 km or less over timescales of ~Gyrs or longer, but having negligible consequences for the silicate mantle, and leaving little macroscopic consequences after circularisation ends (Fig. 1). The reference viscosity of the shell strongly controls the timescale of evolution, which varies between 1-4 Gyr, but these results are otherwise not strongly dependent on chosen interior or thermal properties. We also find that Triton likely reached temperatures >1300 K which might enable formation of an iron core, though not as a result of tides. Ongoing work intends to evaluate the consequences of Andrade rather than Maxwell rheology.

As a result of Triton's progression through spin-orbit resonances and high eccentricity, tidal dissipation is distributed across a wide range of forcing frequencies. The tidal response at these frequencies is dominated by the ice shell, which does not vary by more than an order of magnitude over these frequencies. Hence, we find that the (MacDonald) constant phase lag model used by [8] gives qualitatively accurate results despite the wide range of excited forcing frequencies. This result therefore hinges strongly on (1) the temperature profile in Triton's shell, and (2) the corresponding viscosity values over this temperature range (~30-270 K), and so we encourage future exploration of those properties.

Fig. 1: evolution of Triton's temperature profile over time (a) with and (b) without tidal heating for a shell melting point viscosity of 5e13 Pa.s; the two are indistinguishable after ~2 Gyr. The approximate solidus temperatures of water-ice (273 K) and silicate (1500 K) are marked, as well as temperatures at which one can expect silicate dehydration (800 K) as well as core formation by percolation of iron melt (1310 K) to occur. The stairstep pattern at the shell-ocean boundary is a plotting artefact.

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