Amphitrite: A Twist on Triton's Capture

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Poseidon Poses Plenty of Puzzling Peculiarities

Several attributes of Neptune are difficult to understand. Why does it orbit at 30.1 AU? How did its 3:2 resonance with Pluto and many other Kuiper Belt Objects (KBOs) arise? Why is it more massive than Uranus, yet have a less massive H/He atmosphere? Why does Neptune radiate 2.6 times the energy it receives from the Sun? And especially, why does it have a large satellite resembling a KBO, in a retrograde orbit? Resolution of these mysteries promises profound insights into the formation of Neptune and the entire Solar System.

Explanations for the first few conundrums have already revealed much. It is the 3:2 resonance of Pluto and other KBOs that first suggested Neptune migrated outward $> 10\,\mathrm{AU}$ [1]. The Nice model [2,3] of planetary migration further hypothesizes that all the giant planets formed in a much more compact configuration between 5 and 15 AU, that a $\sim 35\,M_\oplus$ disk of planetesimals orbited from 15-30 AU, and that all were destabilized 4 Gyr ago when Jupiter and Saturn reached a 2:1 resonance. During the destabilization, Neptune and Uranus may have switched orbits; [4] showed that the solar nebula mass distribution implied by the Nice model is more consistent with Neptune forming closer in than Uranus. It would then make sense that Neptune's mass should exceed Uranus's. Still unexplained, though, are Neptune's internal structure and the capture of Triton.

The internal structures of Neptune and Uranus have been modeled by [5], who match their masses, radii and gravitational moments. Uranus was successfuly modeled with $1.5\,M_\oplus$ of H/He gas and an ice density 90% of the 0 K density, consistent with temperatures in the upper ice layers only a factor of 2 higher than the adiabat with $T(1\,\mathrm{bar}) = 75\,\mathrm{K}$. This has been explained by stable stratification in Uranus's ice shell that inhibits convection and traps heat inside Uranus [6]; this is consistent with Uranus's low heat flux. The magnetic dynamos of Uranus and Neptune also suggest no convection interior to $r \approx 0.6 - 0.7R$ in each planet [7]. [5] find two possible configurations for Neptune. The first ("Neptune 1") has denser ice [i.e., 100% of the 0 K density], and more H/He gas ($2.2\,M_\oplus$), with an H_2O/H_2 ratio 150 times solar. The second ("Neptune 2") has less dense ice [i.e., 80% of the 0 K density], less H/He gas ($0.9\,M_\oplus$), and a solar H_2O abundance. [5] favored "Neptune 2" because its composition better matched Uranus's, but the lower density and higher temperature of ice is difficult cannot be explained solely by stable stratification, especially in the face of Neptune's high heat flux.

Triton in mass and density and closely resembles Pluto, and its inclined, retrograde orbit clearly marks it as a captured KBO [8]. Its initial periapse after capture must have been about $7\,R_\mathrm{N}$, and it later circularized by tidal dissipation to its current $14\,R_\mathrm{N}$ orbit [8]. To date the most probable explanation appears to be that Triton was part of a binary KBO that encountered Neptune [9], probably during its outward migration 4 Gyr ago. The other component of the binary carrying off orbital momentum enables Triton's capture, but the model faces difficulties. First, the smaller body of the KBO binary is overwhelmingly favored to be captured, so Triton must be bound to a larger object, but at most < 100 KBOs larger than Triton could have existed in the planetesimals disk [10], and only a very few of them could have been bound to larger KBOs. Second, the approach velocity to Neptune of the KBO binary, v_∞, must not exceed a few times the orbital velocity of Triton; for a Triton-Triton binary, typically $v_\infty < 0.5\,\mathrm{km\,s^{-1}}$ is needed for capture [9]. During Neptune's migration, though, typically $v_\infty \approx 2 - 3\,\mathrm{km\,s^{-1}}$ [12], and even if all Triton-sized KBOs were bound to larger KBOs, Neptune is unlikely to capture a Triton during its migration (< 0.02 probability) [10].

An Amazing Answer to All: Amphitrite

In the Nice model, the giant planets formed much closer to the Sun (at ≈ 5.5, 8.6, 11.5 and 14.2 AU), and formation of additional planets in the planetesimal disk is possible. In particular, [4] has shown a $\approx 2\,M_\oplus$ planet could have formed at about 18 AU. We hypothesize that such a planet did exist, and that Triton was its moon. We call the planet Amphitrite (for many reasons, not least of which is that she was the mother of Triton in Greek mythology). We note that it is far likelier for a $2\,M_\oplus$ Amphitrite to capture a Triton-sized KBO into a wide ($d \sim 10^6\,\mathrm{km}$) orbit (e.g., by three-body (L^3) capture [11]), than it is for Neptune to capture Triton into an orbit with a $7\,R_\mathrm{N}$ periapse.

Since no $2\,M_\oplus$ planet exists, it probably collided with either Uranus or Neptune. Amphitrite is likely to have had close encounters with one or both, but since a direct collision is always rare, repeated passes are needed for a collision. In the Nice model, Neptune migrates through the planetesimal disk at 18 AU much faster than Uranus does later on, affording Amphitrite more opportunities to collide with Uranus than Neptune. We consider both options here.

If Amphitrite had a close encounter with Neptune but missed it, Triton may still be captured. Assuming Amphitrite went on to collide with Uranus, this would explain its large obliquity, for which [12] invoked impact by a $2\,M_\oplus$ body. If the mixture of Amphitrite's rock into Uranus's ice increased its molecular weight and suppressed convection, a Uranus warmer than the Neptune 1 model is understood, and only Neptune's overabundance of H_2O is unexplained, although vigorous convection may be involved. We are currently investigating the probabilities of capture of Triton by Neptune when Amphitrite misses Neptune, and will present results at the conference.

Here we present a preliminary numerical investigation of the second scenario, in which Amphitrite collides with Neptune, using a velocity Verlet integrator we wrote with a timestep of 1 second. We assumed a head-on collision, with a variety of Neptune approach velocities v_∞ (in Triton's orbit plane), and we initialized Triton to be in circular orbit with radius d around Amphitrite, considering $\sim 10^2$ orbital phases for each combination. The results (Figure 1) reveal that the average post-capture periapse $\approx 7\,R_\mathrm{N}$ when $d \approx 40\,R_\mathrm{N}$ and $v_\infty \leq 2\,\mathrm{km\,s^{-1}}$; the probability of capture for these parameters is 25 - 40%.

In this second scenario Uranus naturally traps heat of formation by stable stratification, but Neptune is hotter and described by the Neptune 2 model because of the impact. Amphitrite's impact would have deposited $> 2 \times 10^{33}$ J of heat deep within Neptune, an energy sufficient to supply Neptune's excess heat flux 4.7×10^{15} W [13] for 13 Gyr. The obliquity of Uranus must be explained in some other fashion, and it is unknown what how probable it is to collide directly with Neptune without first losing Triton by binary disruption during earlier passes. Our invesitgations into that problem are also ongoing and will also be presented at the conference.

We conclude that the capture of Triton by Neptune is greatly facilitated if Triton was originally in a wide ($d \sim 1 \times 10^6\,\mathrm{km}$) orbit around a $2\,M_\oplus$ planet (Amphitrite). This planet probably collided with Uranus or Neptune, with significant observational consequences either way. Discrimination of these two scenarios depends on Neptune's internal structure and the fate of Triton during Amphitrite's near misses with Neptune, factors we will discuss at the conference.

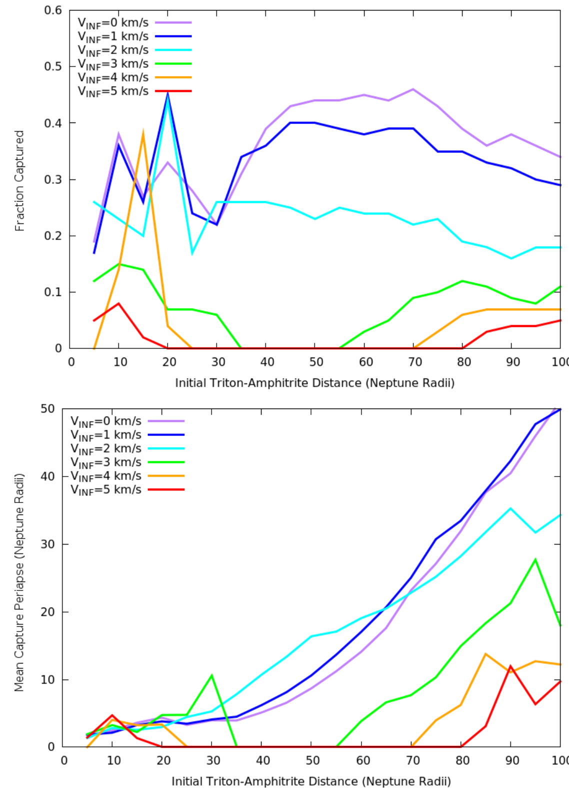

Figure 1: (*Top*) Probability of Triton capture and (*Bottom*) resultant average periapse of Triton, as a function of orbital radius d, for various v_∞.

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