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Serving two masters: Triton as an immigrant planetary moon

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Abstract

Triton, the largest Neptunian satellite, is the only counter-rotating major moon in the solar system. Here we show that Neptune can capture Triton as a member of another planet's satellite system that migrates during a planetary flyby in the early solar system evolution.

1. Introduction

Triton is unique among solar system moons. On a circular orbit at 14 Neptunian radii, it is revolving around the host in a retrograde configuration with an inclination of $157°$. This strongly suggests a capture origin followed by orbital circularisation. Various models have been proposed, e.g., gas-drag, collisions or exchange action, all focusing on capture from heliocentric orbits.

Here we propose a different scenario where Triton forms around another planet and Neptune captures the moon when the two planets encounter each other.

2. Encounter simulations

We embed our encounters in the Nice scenario of early solar evolution [1]. There, an ice giant (IG) encounters all the giant planets and is subsequently ejected by Jupiter [2]. Here we directly create such encounters between the IG and Neptune in a three-body configuration Sun-IG-Neptune [3]. The encounter distance is 0.003 au, the deepest reported in Nice scenario simulations [4] and the mass of the IG is set to be 18 earth masses. 500 such encounters are generated.

The primordial satellite population at the IG is unknown so we place 1100 test moons evenly distributed between 5 and 60 planetary radii, roughly where the major solar system moons reside. These test moons are evolved in each of the 500 encounters as massless test particles. After the encounter, we consider a moon a captive if its Neptune-centric orbit is eccentric. Those test moons subject to high-amplitude Kozai-Lidov oscillations are removed because they collide with Neptune.

3. Results

Out of our $500 \times 1100 = 5.5 \times 10^5$ test moons, $\sim 10\%$are captured by Neptune during the encounter. The distribution of the captives in the semimajor axis (a)-eccentricity (e) and a-inclination (i) planes is shown in Figure 1. As the bottom panel shows, most of the captives have a ranging from tens to hundreds of Neptunian radii ($R_{\rm Nep}$). Their e is typically >0.4. In the top panel, we note a region devoid of moons with $a > 70R_{\rm Nep}$ and $i \sim 90°$, a result of removal due to Kozai-Lidov cycles. The distribution in i is wide and covers the entire range from $0°$ to $180°$.

In the same figure, the observed orbit of Triton is shown as the large grey circle. While its a and i can be reproduced by our capture models, this is not the case for e. Hence, additional factors must be considered to circularise the orbit. Here we take into account the tides induced by Neptune that slowly damps the orbital eccentricity. Moons on tight orbits can be circularised within the age of the solar system (4 Gyr) and those on wide orbits cannot. Following a constant time lag tidal model [5], we plot a line in the (a, e) plane such that all points on it have the same circularisation time of 4 Gyr, as shown in the bottom panel in black.

This tidal circularisation constraint means that our capture model predicts two types of moons. The first, on the left-hand side of this line, consists of moons on circular orbits while those on the right will retain their wide and eccentric orbits well after capture.

During tidal evolution, the orbital angular momentum (AM) of an orbit is quasi-conserved and an object evolves along a constant-AM line. In the bottom panel, we show this line in grey of the AM of Triton, so any moon on the line will become Triton. This grey line crosses the high-density area and is on the left-hand side of the black line–the occurrence rate for Triton's

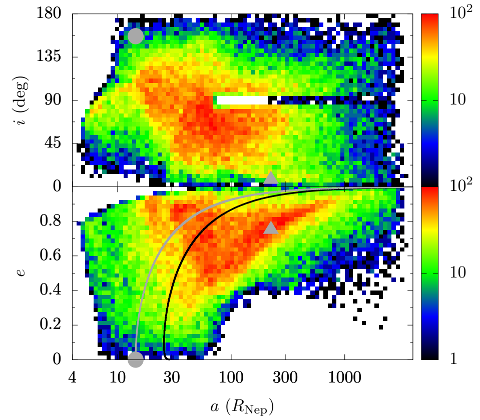

Figure 1: Distribution of captured moons at Neptune in the semimajor axis-inclination and -eccentricity planes. The grey circle is Triton. In the bottom panel, the grey line represents constant angular momentum of that of Triton. The black line marks the limiting case where orbits can be circularised by tides just within the age of the solar system. Nereid, another Neptunian moon, is shown as the grey triangle for reference.

AM is high in our simulations and such moons are circularised within 4 Gyr. Thus, Triton can be reproduced by our capture model.

Finally, we note that Nereid, another moon of the Neptunian system, can also be captured in our simulations. In Figure 1, this moon, as the grey triangle shows, sits comfortably in the high-probability region of our captured orbits in the (a, e) plane.

4. Summary

We have simulated close encounters between Neptune and an ice giant with its own a primordial satellite system. During these encounters, $\sim 10\%$ of the moons are captured by Neptune onto highly eccentric orbit. Those captured onto tight orbits can be efficiently circularised by tides while those far-out cannot.

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