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Triton's Evolution with a Primordial Neptunian Satellite System

Raluca Rufu[1] and Robin M. Canup[2,3]
[1] Department of Earth and Planetary Sciences, Weizmann Institute of Science, Rehovot 76100, Israel; raluca.rufu@weizman.ac.il
[2] Southwest Research Institute, Boulder, CO 80302, USA
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Abstract

The Neptunian satellite system is unusual. The major satellites of Jupiter, Saturn, and Uranus are all in prograde, low-inclination orbits. Neptune on the other hand, has the fewest satellites, and most of the system's mass is within one irregular satellite, Triton. Triton was most likely captured by Neptune and destroyed the primordial regular satellite system. We investigate the interactions between a newly captured Triton and a prior Neptunian satellite system. We find that a prior satellite system with a mass ratio similar to the Uranian system or smaller has a substantial likelihood of reproducing the current Neptunian system, while a more massive system has a low probability of leading to the current configuration. Moreover, Triton's interaction with a prior satellite system may offer a mechanism to decrease its high initial semimajor axis fast enough to preserve small irregular satellites (Nereid-like) that might otherwise be lost during a prolonged Triton circularization via tides alone.

Key words: planets and satellites: dynamical evolution and stability – methods: numerical

1. Introduction

Models of giant planet gas accretion and satellite formation suggest that gas giants may typically have prograde regular satellite systems formed within circumplanetary gas disks produced during their gas accretion, consistent with the general properties of the satellite systems of Jupiter and Saturn (e.g., Stevenson et al. 1986; Lubow et al. 1999; Canup & Ward 2002; Mosqueira & Estrada 2003; Sasaki et al. 2010; Ogihara & Ida 2012). The origin of Uranus' satellites remains unclear, as they may have similarly formed as a result of Uranus' limited gas accretion (e.g., Pollack et al. 1991; Mosqueira & Estrada 2003; Canup & Ward 2006), or as a result of a giant impact (e.g., Slattery et al. 1992), or a combination of both (Morbidelli et al. 2012).

Neptune has substantially fewer and mostly smaller satellites than the other gas planets. The one massive satellite, Triton, is highly inclined, therefore it was likely captured from a separated KBO binary (Agnor & Hamilton 2006). If Neptune had a primordial (pre-Triton) satellite system with a mass ratio of $m_{\rm sat}/M_{\rm Nep} \sim 10^{-4}$ as suggested by Canup & Ward (2006), then Triton's mass approaches the minimum value required for a retrograde object to have destroyed the satellite system. Thus, the existence of Triton places an upper limit on the total mass of such a primordial system.

The high initial eccentricity of Triton's orbit may decay by tidal dissipation in less than 10^9 years (Goldreich et al. 1989; Nogueira et al. 2011). However, the perturbations from an eccentric Triton destabilize small irregular satellites (Nereid-like) on a timescale of 10^5 years (Nogueira et al. 2011). Moreover, Ćuk & Gladman (2005) argue that Kozai cycles increase Triton's mean pericenter, increasing the circularization timescale beyond the age of the solar system. That study proposes that perturbations on pre-existing prograde satellites induced by Triton lead to mutual disruptive collisions between the pre-existing satellites. The resulting debris disk interacts with Triton and drains angular momentum from its orbit, reducing the circularization timescale to less than 10^5 years. Yet, it is unclear whether Triton can induce mutual collisions among such satellites before it experiences a disruptive collision. Due to its retrograde orbit, collisions between Triton and a prograde moon would generally have higher relative velocities than those between two prograde moons. A disruptive collision onto Triton is inconsistent with its current inclined orbit (Jacobson 2009), as Triton would tend to re-accrete in the local Laplace plane.

The objective of this study is to explore how interactions (scattering or collisions) between Triton and putative prior satellites would have modified Triton's orbit and mass. We evaluate whether the collisions among the primordial satellites are disruptive enough to create a debris disk that would accelerate Triton's circularization, or whether Triton would experience a disrupting impact first. We seek to find the mass of the primordial satellite system that would yield the current architecture of the Neptunian system. If the prior satellite system is required to have a substantially different mass ratio compared to Jupiter, Saturn, and Uranus, this would weaken the hypothesis that all the satellites in these systems accreted in a similar way. Alternatively, more stochastic events (e.g., giant impacts) may have a greater influence on satellite formation for icy giants.

2. Methods

We perform N-body integrations using SyMBA code (Duncan et al. 1998, based on previous work of Wisdom & Holman 1991) of a newly captured Triton together with a hypothetical prograde satellite system for 10^7 years including effects of Neptune's oblateness. The SyMBA code can effectively resolve close encounters among orbiting bodies, and perfect merger is assumed when an impact is detected.

We consider a primordial prograde satellite system composed of four satellites with similar mass ratios compared to Neptune as Ariel, Umbriel, Titania, and Oberon to Uranus (Laskar & Jacobson 1987). The total mass ratio of the satellite system is 1.04×10^{-4} (hereafter $M_{\rm USats}$), in agreement with the common mass ratio for gaseous planets predicted by Canup & Ward (2006). Triton's initial orbits are chosen from previous

[3] Planetary Science Directorate.

Table 1
Dynamical Survival Results: a_T, Triton's Initial Semimajor axis in Neptune Radii, q_T, Triton's Initial Pericenter in Neptune Radii, inc_T, Triton's Initial Inclination

#Set	$a_T\,[R_{\mathrm{Nep}}]$	$q_T\,[R_{\mathrm{Nep}}]$	inc_T[deg]	# Triton's Survival			# Triton's Fall onto Planet			# Triton's Escape		
				$0.3M_{\mathrm{USats}}$	M_{USats}	$3M_{\mathrm{USats}}$	$0.3M_{\mathrm{USats}}$	M_{USats}	$3M_{\mathrm{USats}}$	$0.3M_{\mathrm{USats}}$	M_{USats}	$3M_{\mathrm{USats}}$
1[a]	300	8.1	105	9	8	2	0	1	6	1	1	2
2[a]	300	8.1	157	10	7	3	0	3	7	0	0	0
3	300	8.1	157	10	0	1	0	10	6	0	0	3
4	1004	8.0	157	9	0	0	0	8	7	1	2	3
5	1004	8.0	105	6	4	0	1	2	4	3	4	6
6	128	8.0	157	10	2	0	0	8	10	0	0	0
7	128	8.0	105	10	5	2	0	5	7	0	0	1
8	512	8.0	157	9	1	1	0	7	5	1	2	4
9	512	8.0	105	8	4	1	0	2	5	2	4	4
10	2000	8.0	157	1	1	0	0	2	1	9	7	9
11	2000	8.0	105	2	2	1	0	2	1	8	6	8
12	300	6.8	105	10	3	2	0	2	5	0	5	3
13	512	8.0	175	10	0	0	0	9	9	0	1	1
14	300	6.8	175	10	0	0	0	10	8	0	0	2
15[a]	512	8.0	157	10	7	0	0	2	9	0	1	1
16[a]	512	8.0	105	10	7	1	0	0	3	0	3	6
17	512	12.5	157	10	4	2	0	5	5	0	1	3
18	512	17.5	157	10	6	1	0	2	4	0	2	5
19	1004	29	157	10	9	1	0	0	5	0	1	4
20	1004	37.9	157	10	9	5	0	0	0	0	1	5

Note.
[a] Semimajor axis are similar to Ariel, Umbriel, Titania, and Oberon.

studies of typical captured orbits (Nogueira et al. 2011; see Table 1 for full list of initial conditions). We choose to test three retrograde initial inclinations (105°, 157°, 175°). Tidal evolution over the simulated time is small and thus neglected (Nogueira et al. 2011). For each set of initial conditions, 10 simulations were performed with randomly varying longitude of ascending nodes, argument of periapsis, and mean anomaly of all the simulated bodies. In 16 sets of initial conditions, the assumed primordial satellites have the same ratio between the semimajor axis and planet's Hill sphere as Uranus's satellites. In four sets of initial conditions, the exact semimajor axes of Uranus's satellites are assumed. Using the same initial orbital parameters, we perform additional simulations with two different satellite system total mass ratios, 0.35×10^{-4} and 3.13×10^{-4}, corresponding to $0.3\ M_{\mathrm{USats}}$ and $3\ M_{\mathrm{USats}}$, respectively. Overall, our statistics include 200 simulations for each satellite mass ratio.

2.1. Disruption Analysis

We use disruption scaling laws, derived by Movshovitz et al. (2016) for non-hit-and-run impacts between two gravity-dominated bodies, to estimate whether the impacts recorded by the N-body code are disruptive. The scaling laws identify impacts that would disperse half or more of the total colliding material, regarded hereafter as disruptive collisions. For head-on impacts, the minimum required kinetic energy (K^*) to disrupt the target has a linear relation with the gravitational binding energy of the colliding bodies (U; Movshovitz et al. 2016),

$$K^* = c_0 U \tag{1}$$

where c_0 is the slope derived for head-on impacts ($c_0 = 5.5 \pm 2.9$).

Higher impact angles require higher energies to disrupt a body, as the velocity is not tangential to the normal plane. A modified impact kinetic energy is required to incorporate the geometric effects,

$$K_\alpha^* = \left(\frac{\alpha M_1 + M_2}{M_1 + M_2}\right) K^* \tag{2}$$

where α is the volume fraction of the smaller body (M_2) that intersects the second body (M_1; Movshovitz et al. 2016; Leinhardt & Stewart 2012). The disrupting relation transforms to

$$K_\alpha^* = cU \tag{3}$$

where c is the geometrical factor derived from the collision outcomes with three tested angles. The collisions were tested on a limited number of impacting angles (direction of velocity relative to the line connecting the centers at contact, 0°, 30°, and 45°); therefore, we assume that the relation of c on the impact angle (θ) is given by the following step function:

$$c = c_0 \begin{cases} 1, & \theta < 30^\circ, \\ 2, & 30^\circ \leqslant \theta < 45^\circ. \\ 3.5, & \theta \geqslant 45^\circ \end{cases} \tag{4}$$

It should be noted that ejected material from a satellite collision can escape the gravitational well of the colliding objects if it has enough velocity to expand beyond the mutual Hill sphere. For the typical impacts observed, the required velocity to reach the Hill sphere is $\sim 0.9 V_{\mathrm{esc}}$, where V_{esc} is the two-body escape velocity. The binding energy used in Equation (3) to determine the disruption scales as $\sim V_{\mathrm{esc}}^2$;

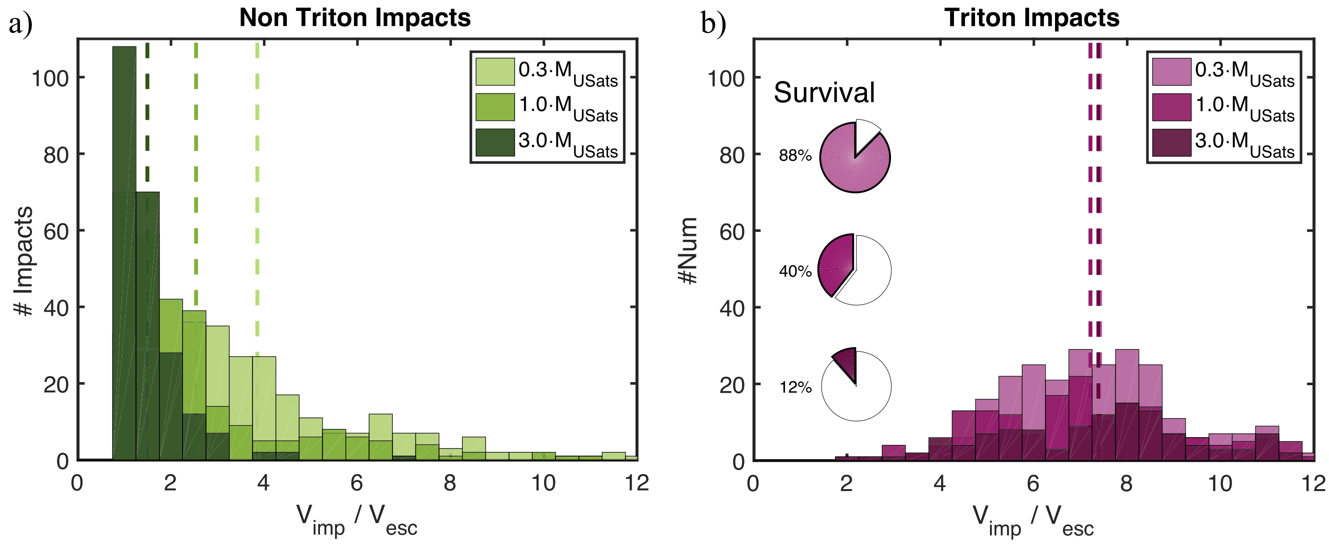

Figure 1. Distribution of impact velocities between the primordial satellites (left) and onto Triton (right). The velocities are normalized by the mutual escape velocity of the impacting bodies. The dashed lines represent the mean of the distributions for each assumed primordial system mass (increasing mass represented by a darker color).

therefore, the required energy to disrupt orbiting bodies may be reduced $\sim 0.8 K_{\alpha}^{*}$. Hence, the disruptive scaling laws used may somewhat overestimate the disrupting energy required, but not too substantially.

3. Results

3.1. Dynamical Survival

In the 200 simulations with the Uranian satellite system mass ratio ($M_{\mathrm{USats}} \equiv 1.04 \times 10^{-4}$), we find the overall likelihood of Triton's survival after 10^7 years is $\sim$40%. Different sets of initial conditions have different probabilities for Triton's loss either by escaping the system or falling onto Neptune. For example, a highly inclined initial Triton (175°) does not survive more than 10^4 years, due to the near alignment of its orbit with Neptune's equatorial plane, which contains the prograde satellites. In this case, after a final Triton-satellite collision, the orbital angular momentum of the merged pair is small, leading to collapse onto Neptune. However, with a lighter satellite system ($0.3 M_{\mathrm{USats}}$), the post-impact angular momentum is high enough and Triton survives. In the cases in which Triton survives, it is usually the last survivor (or one of two remaining satellites if Triton's initial pericenter is large), reproducing the low number of Neptunian satellites. Overall, Triton's dynamical survivability decreases with increasing mass of pre-existing satellite system, 12% for the heavier satellite system with 3 M_{USats}, and 88% for the lighter satellite system with 0.3 M_{USats}.

Out of the surviving cases, Triton usually ($\sim$90%) experienced at least one impact. Due to Triton's initial retrograde orbit, mutual impacts between the primordial satellites (Figure 1(a)) have a significantly lower velocity compared to the collisions between Triton and a primordial satellite (Figure 1(b)). The mean velocity for non-Triton impacts decreases with increasing mass of the pre-existing satellite system, as Triton is less able to excite the more massive system.

It should be noted that the number of Triton impacts decreases with increasing satellite mass, because Triton is lost earlier as the mass pre-existing satellites increases, and therefore, fewer events are recorded.

3.2. Disrupting Impacts

For satellite systems with a Uranian mass ratio, impacts onto Triton are more disruptive (18% of impacts; pink circles with black dots, see Figure 2(b)) than mutual collisions among the primordial satellites (3%; green triangles with black dots, see Figure 2(b)). With decreasing satellite mass, disruption of Triton is inhibited as the mass ratio decreases. Overall, 33% of tested cases with M_{USats} (81% with $0.3 M_{\mathrm{USats}}$ and 10% with $3 M_{\mathrm{USats}}$) resulted in a stable Triton that did not encounter any disrupting impacts throughout the evolution. Although Triton does experience disruption in some cases, a satellite system of 0.3–1 M_{USats} has a substantial likelihood for Triton's survival without the loss of Triton's initial inclination by disruption and reaccretion into the Laplace plane.

With decreasing satellite mass, disruption for non-Triton bodies increases somewhat as the typical impact velocity increases (8% for $0.3 M_{\mathrm{USats}}$ and none for $3 M_{\mathrm{USats}}$). The low rate of primordial satellite disruption calls into question the formation of a debris disk from the primordial satellites envisioned by Ćuk & Gladman (2005) to rapidly circularize Triton. Moreover, assuming that a disruptive impact between the primordial satellites leads to the formation of a debris disk, the rubble will quickly settle onto the equatorial plane and re-accrete to form a new satellite. The timescale of reaccretion can be estimated by the geometric mass accumulation rate (Banfield & Murray 1992)

$$\tau_{acc} \sim \frac{m}{\pi r^2 \sigma_s \Omega} \qquad (5)$$

where m is the mass of the satellite, r its radius, σ_s is the surface density of the debris disk, and Ω its orbital frequency. For typical debris ejection velocities $\sim V_{\mathrm{esc}}$ (e.g., Benz & Asphaug 1999), the width of the debris ring created by a disrupting impact is estimated by $\Delta a \sim ae \sim a\frac{V_{\mathrm{esc}}}{V_{\mathrm{orb}}}$, where a is the semimajor axis of the debris, e is the eccentricity of the

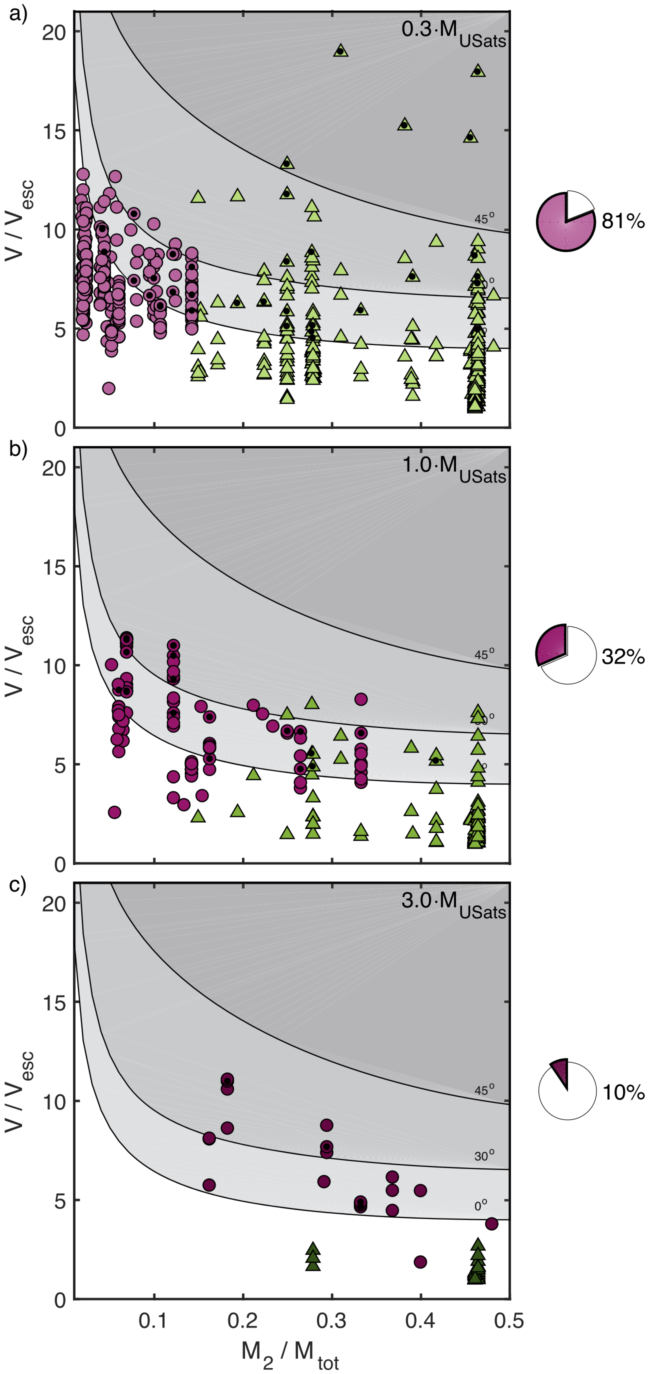

Figure 2. Impact phase space for all Triton-surviving cases with different primordial satellite mass. Mass ratio between the smallest body and the total impacting mass as a function of normalized impact velocity for impact onto Triton (pink circles) and between the primordial satellites (green triangles). The black dots represent disrupting impacts calculated using Movshovitz's disruption laws (Movshovitz et al. 2016). For simplicity, the disruptive phase space for 0°, 30°, and 45° are added as gray areas. In this way, all impacts on the bottom left of the figure are non-disruptive and darker areas represent higher disruption probability. The pie chart on the right indicates the percentage of cases where Triton dynamically survived and did not experience any disrupting impact.

debris, V_{orb} is the orbital velocity, and $\frac{V_{esc}}{V_{orb}}$ is proportional to the eccentricity of the debris induced by the impact. Rearranging the equation above for a disrupted satellite of mass m dispersed across an area of $2\pi a\Delta a$, we obtain:

$$\tau_{acc} \sim \frac{2a^2}{r^2\Omega}\cdot\frac{V_{esc}}{V_{orb}}. \qquad (6)$$

Assuming an impact between two primordial satellites equivalent to the mass of Oberon and Titania at a distance of $10R_{Nep}$, the timescale for reaccretion is $\sim 10^2$ years. The reaccretion timescale is smaller than the evaluated eccentricity decay time for Triton of 10^4–10^5 years (Ćuk & Gladman 2005). Thus, the debris disk, even if it formed, would likely re-accrete before Triton's orbit circularized.

3.3. Final Triton's Orbits

In order to ensure stabilization of Nereid (and Nereid-like satellites), Triton's apoapse needs to decrease to within Nereid's orbit in 10^5 years (Ćuk & Gladman 2005; Nogueira et al. 2011). Otherwise, Neptune's irregular satellites must be formed by an additional subsequent process (e.g., Nogueira et al. 2011). Torques produced by the Sun and Neptune's shape are misaligned by Neptune's obliquity (30°), causing a precession of the argument of pericenter (Kozai oscillations). For large orbits, the Kozai mechanism induces oscillations (period $\sim 10^3$ years) in the eccentricity and inclination such that the z-component of the angular momentum ($H_z = \sqrt{1-e^2}\cos I$, where I is the Triton's inclination with the respect to the Sun) is constant. For retrograde orbits, the eccentricity and inclination oscillate in phase; therefore, the maximum inclination occurs at the maximum eccentricity. For small orbits ($<70R_{Nep}$; Nogueira et al. 2011), the torque induced by Neptune's shape is larger than the Kozai cycles induced by the Sun, and Triton's tidal decay occurs with approximately constant inclination. Here, we seek to identify Triton analogs with final apoapses smaller than Nereid's pericenter (55 R_{Nep}; Jacobson 2009) and inclinations close to Triton's current inclination of 157°, as this will remain constant in subsequent tidal circularization.

As seen previously, the smallest pre-existing satellite system mass ratio has a high rate of survival, and about half of the Triton's analogs are within Nereid's orbit with minimal inclination change (Figure 3(a)). As the primordial satellites mass increases, the percentage of Triton analogs inside Nereid's orbit increases, although Triton's inclination change is larger. Moreover, due to the small survivability rate, only a small number of cases with $3M_{USats}$ fulfilled all of the required conditions to be regarded as successful Triton analogs that may allow Nereid-like satellites to survive (Triton's dynamic survival with no disruption, on a small and inclined orbit). Typically, Triton analogs that did not experience any impact have larger final orbits, as scattering alone does not effectively decrease the orbital apoapse.

In addition, we roughly estimated the effect of solar perturbations on Triton's orbital evolution by performing additional simulations that include Triton, Neptune, and the Sun (positioned on an inclined orbit relative to Neptune's equatorial plane in order to mimic the planet's obliquity; see Appendix B for more details). Due to induced eccentricity oscillations, Triton spends only $\sim$10% of the time in the region populated by primordial satellites (Ćuk & Gladman 2005, Figure 1). Out of the recognized successful cases in Figure 3, $\sim$30%–50% are already within Nereid's orbit after 10^4 years (see Figure 6). Even though Kozai could lengthen the time of

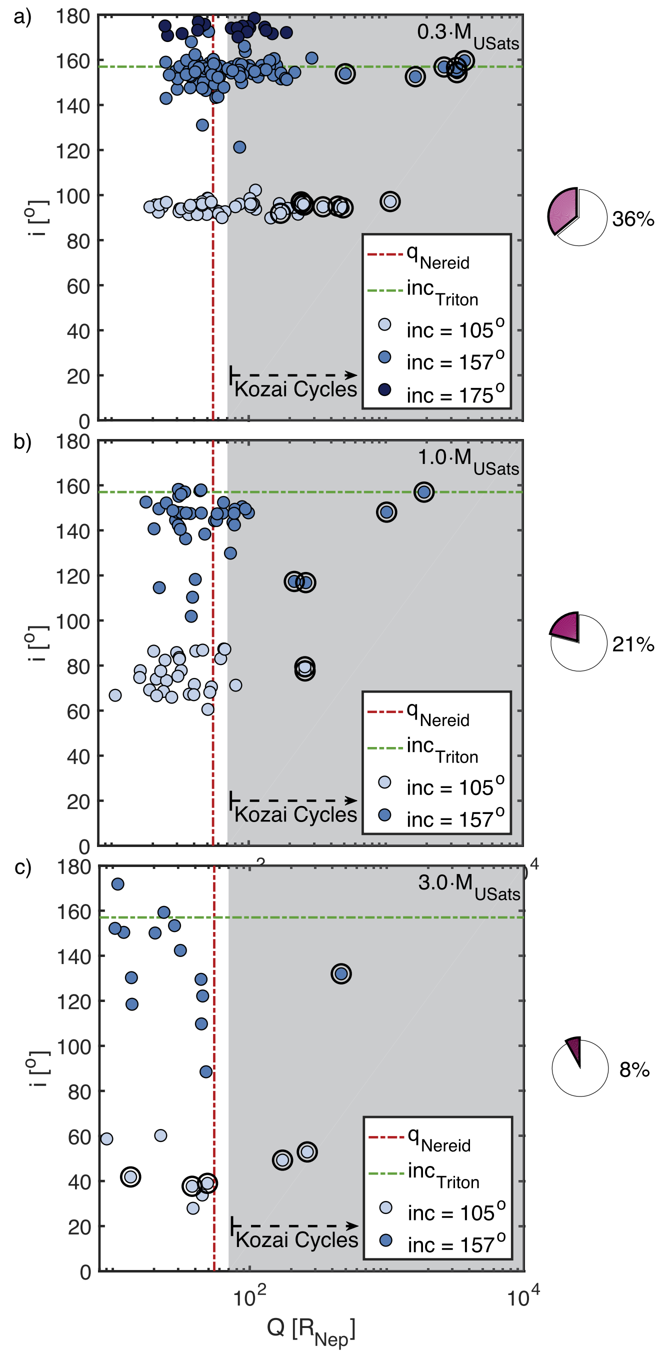

Figure 3. Final Triton orbits. Triton's final apoapsis in Neptune radii vs. its final orbital inclination for different initial inclinations. The vertical/horizontal dashed line represents the current Nereid's periapsis/Triton's current inclination. The light gray region represents the regions where Kozai perturbations are significant; for lower orbits, tidal evolution proceeds with constant inclination (Nogueira et al. 2011). Simulated Triton analogs that did not experience any impacts are indicated by the black circles. The pie charts on the right indicate the percentage of cases where Triton dynamically survived, did not experience any disrupting impact, and had a final orbit within Nereid's current orbit.

orbit contraction by a factor of 10, Triton's orbit in these cases would still decrease within Nereid's orbit in $\leqslant 10^5$ years. Therefore, even if solar perturbations were included in the numerical scheme, Nereid would still likely be stable in these cases. Additional studies are needed to determine the specific details induced by the Kozai mechanism in the first part of Triton's evolution, when the semimajor axis is still large, in order to fully evaluate the stability of pre-existing irregular moons, including the effects of a pre-existing prograde satellite system.

4. Discussion

We performed dynamical analyses of a newly captured Triton together with a likely primordial Neptunian satellite system. Most of the recorded impacts (onto Triton or between the primordial satellites) are not disruptive; therefore, we conclude that the formation of a debris disk composed of primordial satellite material is unlikely for the assumed initial conditions. Moreover, if a debris disk is indeed formed outside the Roche limit, its reaccretion timescale is $\sim 10^2$ years, smaller than Triton's orbital decay by the debris disk, which is 10^4–10^5 years (Ćuk & Gladman 2005).

We find that a primordial satellite system of $>0.3\ M_{\rm USats}$ decreases Triton's orbit within Nereid's via collisions and close encounters. Triton's interactions with the primordial system enhances its circularization and may preserve the small irregular satellites (Nereid-like), that might otherwise be lost during a protracted Triton circularization via tides alone, echoing Ćuk & Gladman (2005)'s findings, although through a different mechanism. The Kozai mechanism may prolong the timing of such impacts; however, we found cases where Triton's circularization still appears fast enough for Nereid's stability.

Moreover, we find that a primordial satellite system of 0.3–1 $M_{\rm USats}$ has a substantial likelihood for Triton's survival while still maintaining an initial high inclination. Higher mass systems have a low probability of reproducing the current system ($\leqslant$10%). We conclude that a primordial satellite system of a mass ratio comparable to that of Uranus's current system appears consistent with the current Neptunian system and offers a means to potentially preserve pre-existing irregular Nereid-like satellites.

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Software: SyMBA (Duncan et al. 1998).

Appendix A
Timing of Impacts

The bodies start colliding after $\sim 10^2$–10^3 years (Figure 4(a)). The first recorded impact is usually among the primordial satellites, consistent with previous estimations (Banfield & Murray 1992; Ćuk & Gladman 2005). In a small number of cases, the primordial satellites did not impact themselves (horizontal markers inside the gray area), but Triton cannibalized the entire system. Usually, a first Triton impact will lead to a primordial impact soon after (markers that are above but close to the red line). Moreover, Triton will encounter the last impact in

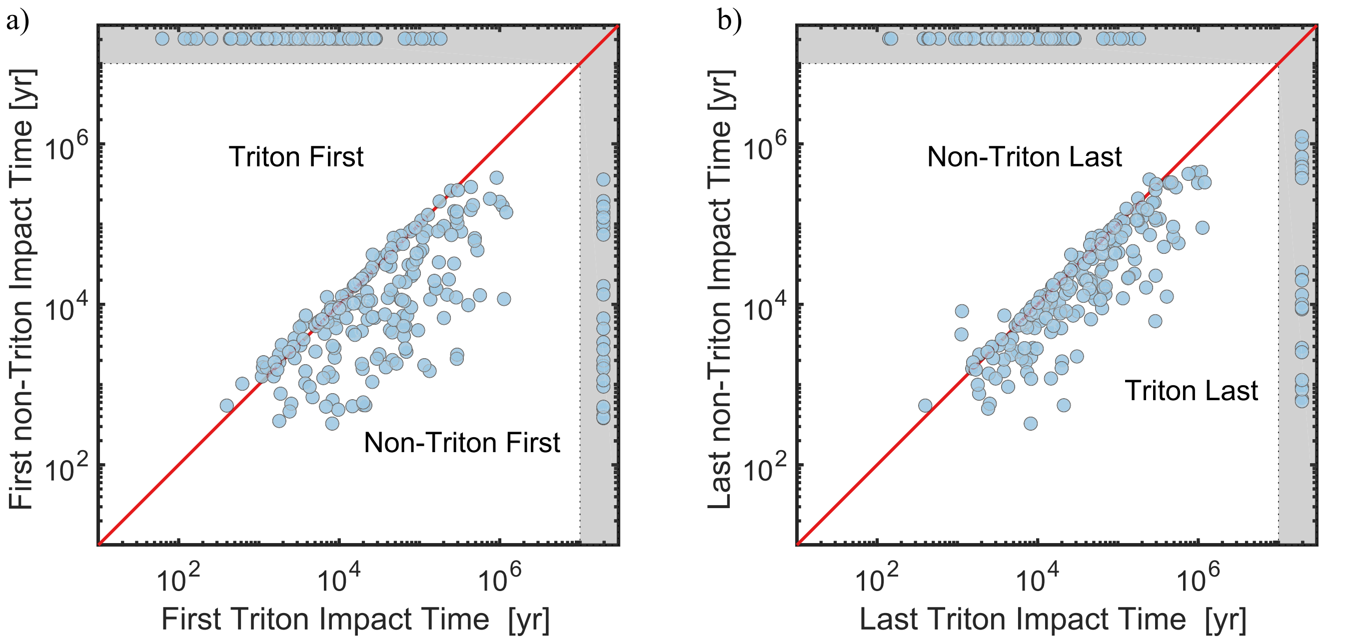

Figure 4. (a) The first impact onto Triton vs. the first impact between primordial satellites for the Triton-surviving cases. Markers that are above/bellow the red line represent cases where Triton/primordial satellites experience the first impact. (b) The last impact onto Triton vs. the first impact between primordial satellites for the Triton-surviving cases. Markers that are above/bellow the red line represent cases where primordial satellites/Triton experience the first/last impact. Cases where primordial satellites/Triton did not encounter any impact are represented by the horizontal/vertical gray area.

most of the scenarios (Figure 4(b)). All impacts (Figure 4(b)) occur within the first $\sim 10^6$ years of the simulation while the difference between most impacts is 10^3–10^4 years.

Appendix B
Solar Perturbations

In order to estimate the effect of perturbation induced by the Sun, we performed simulations using a Bulirsch-Stoer integrator to simulate Triton as a massless particle orbiting Neptune with no satellites. The Sun is added as a secondary orbiting body with an inclined orbit equal to Neptune's obliquity. We used the same initial conditions for Triton as used before and checked whether Triton remains in orbit after 10^7 years.

For the lower inclined orbits (105°), we find that in 88% of the cases Triton fell onto Neptune, as the Kozai mechanism is strongest when the torque is perpendicular ($I \sim 90°$; Nogueira et al. 2011). Moreover, the timing of Triton's lost due to Sun perturbations is usually earlier than the collision timescale with a primordial satellite system of M_{USats} (markers bellow the red line in the white region of Figure 5). For the higher inclined orbits (157°/175°), we find significantly lower percentages (26%/10%) of Triton's loss. Due to eccentricity perturbations induced by the Sun, only 10% of Triton's orbits will cross the primordial satellite system (Ćuk & Gladman 2005). Therefore, Triton's collisions with the primordial satellites will be prolonged by roughly a factor of 10 relative to previous simulations that do not include solar perturbations.

Figure 6 shows the momentary Triton's orbit at 10^4 years after the start of the simulation. We find that $\sim$30%–50% of

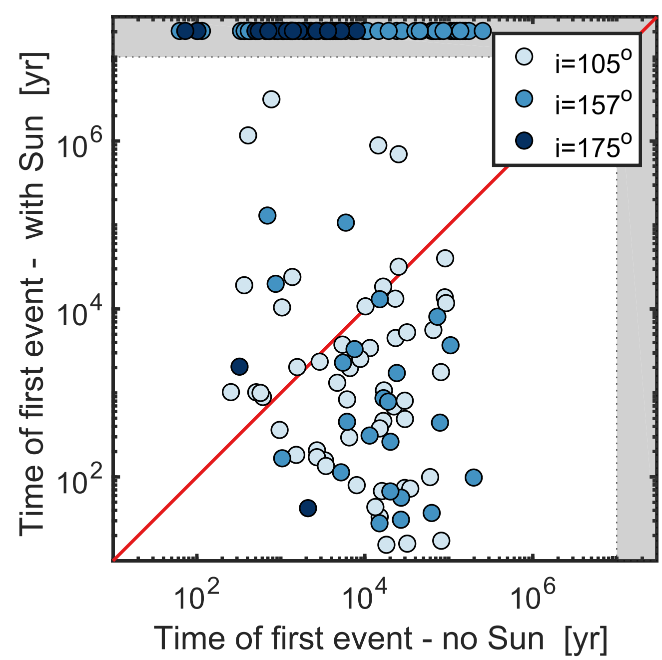

Figure 5. Timing of the first event in the simulation with a primordial system of M_{USats} vs. Triton's loss time due to Kozai cycles. Markers that are below the red line represent cases where loss due to Kozai perturbations is faster than the satellite dynamics. Cases where Triton survived the Sun perturbation simulations are represented in the horizontal gray area.

successful cases in Figure 3 are already within Nereid's orbit at this time. In these cases, Triton's prolonged evolution should still be consistent with Nereid's presence in its current orbit, even considering Kozai oscillations.

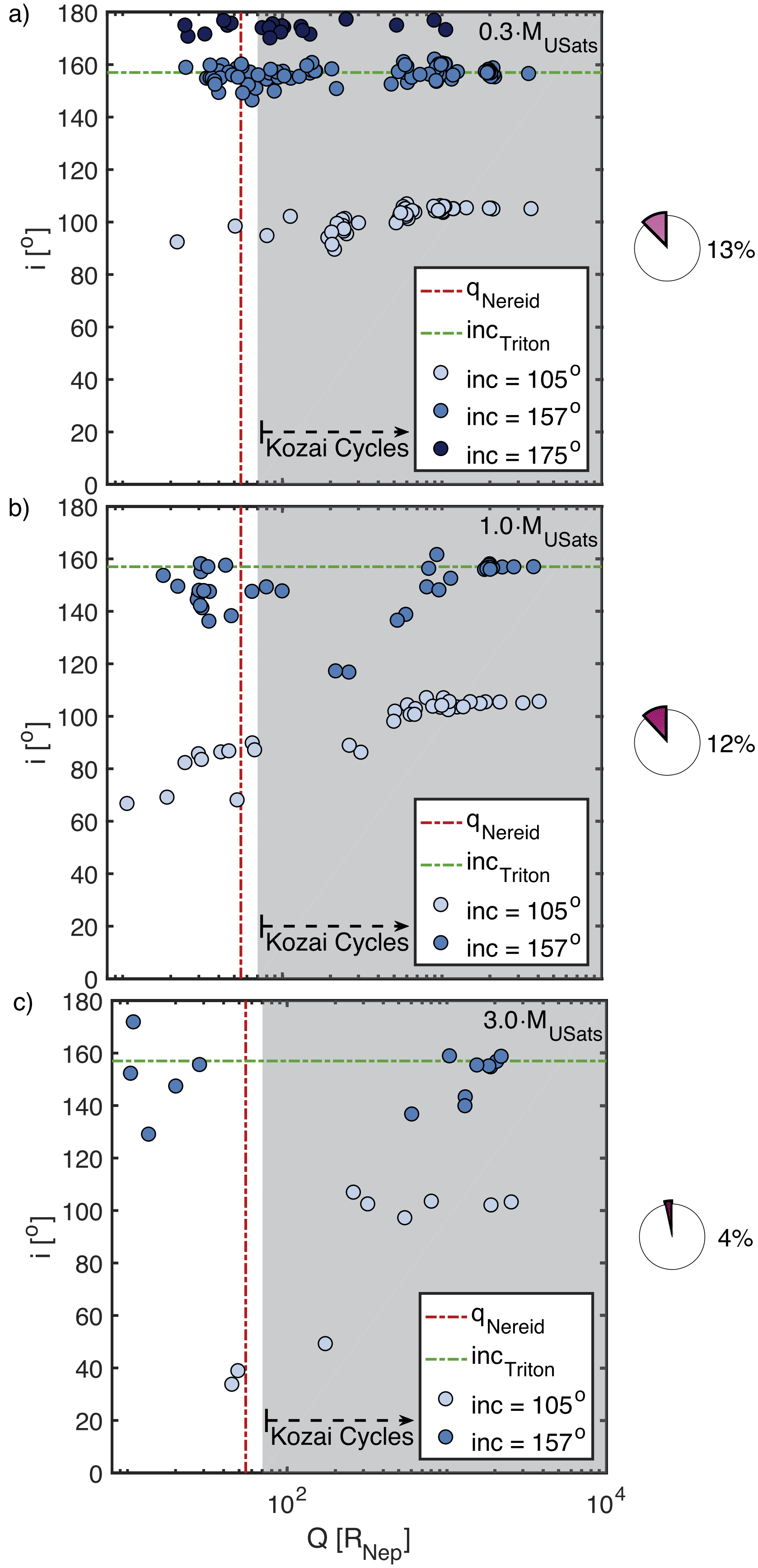

Figure 6. Triton's apoapsis in Neptune radii vs. its orbital inclination for different initial inclinations at 10^4 years. The vertical/horizontal dashed line represents the current Nereid's periapsis/Triton's current inclination. The light gray region represents the regions where Kozai perturbations are significant. The pie charts on the right indicate the percentage of cases where Triton dynamically survived and had an orbit within Nereid's current orbit after 10^4 years of simulated time.

ORCID iDs

Raluca Rufu https://orcid.org/0000-0002-0810-4598

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