Neptune's Story

P. Goldreich, N. Murray, P. Y. Longaretti, D. Banfield

It is conjectured that Triton was captured from a heliocentric orbit as the result of a collision with what was then one of Neptune's regular satellites. The immediate post-capture orbit was highly eccentric with a semimajor axis $a \sim 10^3 R_N$ and a periapse distance r_p that oscillated periodically above a minimum value of about $5R_N$. Dissipation due to tides raised by Neptune in Triton caused Triton's orbit to evolve to its present state in $\lesssim 10^9$ years. For much of this time Triton was almost entirely molten. While its orbit was evolving, Triton cannibalized most of the regular satellites of Neptune and also perturbed Nereid, thus accounting for that satellite's highly eccentric and inclined orbit. The only regular satellites of Neptune that survived were those that formed well within $5R_N$ and they move on inclined orbits as the result of chaotic perturbations forced by Triton. Neptune's arcs are confined around the corotation resonances of one of these inner satellites. The widths and lengths of the arcs imply that the satellite's radius is at least $30/(\sin i)^{2/3}$ kilometers for $i \lesssim 1$, where i is the angle of inclination.

Neptune's satellite and ring systems differ from those of other giant planets. In place of a series of regular satellites, Neptune has a large inner satellite, Triton, which moves in a retrograde sense on a circular and inclined orbit. Instead of complete rings, Neptune possesses a collection of ring arcs. What makes Neptune so different? Our answer is the subject of this article.

There are two known satellites of Neptune: Triton and Nereid. Triton, of comparable size to the moon, moves on a retrograde orbit with semimajor axis (in Neptune radii, R_N) $a \approx 14R_N$, eccentricity $e \lesssim 0.005$, and inclination $i \approx 21°$ to Neptune's equator plane. The mass M_T and radius R_T of Triton are both poorly known. Nereid is much smaller and has the most eccentric orbit of any satellite with $a \approx 219R_N$, $e \approx 0.75$, and $i \approx 28°$ to the orbit plane of Neptune. Neptune's sparse and irregular satellite system stands in contrast to the rich and regular satellite systems of Jupiter, Saturn, and Uranus. In addition, Triton is anomalously large in comparison to the satellites orbiting Uranus, a planet that is Neptune's virtual twin (*1*). We take the Triton-Neptune mass ratio $\mu \equiv M_T/M_N \approx 3 \times 10^{-4}$ and $R_T \approx 1.5 \times 10^3$ km as nominal values.

Particulate material, prevented by tidal gravity from collecting into satellites, orbits close to all giant planets. Jupiter's tenuous rings, Saturn's broad bright rings, and Uranus's narrow dark rings differ greatly in morphology but all completely encircle their parent planet. Again, Neptune is an exception; instead of complete rings it possesses a system of incomplete arcs, each of order tens of kilometers in width and perhaps no more than a few thousand kilometers in length (*2, 3*).

Voyager 2 will complete its tour of the outer solar system with a flyby of Neptune in August 1989. Here, we assess our knowledge of that planet's satellite and ring systems before Voyager makes contact. If Neptune were not mute, this is the story it might tell.

Capture of Triton. Triton was undoubtedly born in a flat disk of material and only later came to occupy the inclined orbit on which it currently moves. Here we explore the possibility that Triton formed on a heliocentric orbit and was subsequently captured by Neptune (*4, 5*). A number of possible mechanisms might have been responsible for the initial capture of Triton by Neptune. For reasons that will become clear later, we favor the idea that Triton's capture followed its physical collision with a regular satellite of Neptune.

The largest orbits with periapses close to Neptune have apoapses at distances comparable to those of Neptune's inner and outer collinear Lagrange points at $r \approx (M_N/3M_\odot)^{1/3} \approx 4.5 \times 10^3 R_N$ ($M_\odot$ is the solar mass). Triton could have been captured onto an extended orbit of this type if it had collided with a regular inner satellite whose mass was a few percent of its own. Such a collision would have dissipated enough orbital energy to allow the capture of Triton but too little to destroy it. The satellite would have been devoured by Triton.

To assess the plausibility of such an event, let us assume that Neptune was formed by the accumulation of several thousand bodies of size comparable to Triton. Gravitational focusing implies that the number of bodies approaching within distance r from the center of Neptune increases in direct proportion to r. Thus, more than 10^4 objects as large as Triton might have passed within $10R_N$ of Neptune during its formation. If we suppose that, before the capture of Triton, Neptune had a satellite system similar to that of Uranus, the probability of a collision during a close approach would have been about 10^{-5}. Thus, the overall probability of capture of a large satellite could have been as large as several tens of percent. This crude estimate is encouraging and suggests that finding one large captured satellite among the outer planet satellite systems is quite reasonable.

Tidal evolution of Triton's orbit. It is striking that Triton's orbit, while inclined and retrograde, is circular. Dissipation associated with tides raised in a satellite by a planet tends to damp both eccentricity and inclination (*6, 7*). Inclination damping is much slower than eccentricity damping because the satellite's oblateness causes its spin vector to remain nearly parallel to the orbit normal as the latter precesses with respect to the planet's equatorial plane (*8*).

The authors are at the California Institute of Technology, Pasadena, CA 91125.

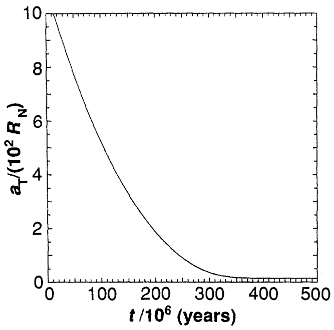


Fig. 1. Evolution of Triton's semimajor axis as a function of time due to tidal dissipation.

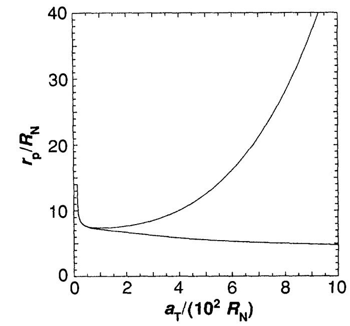


Fig. 2. Evolution of the minimum and maximum values of Triton's periapse distance as a function of its semimajor axis owing to the combined influence of solar perturbations and tidal dissipation. The periapse distance oscillates between the two curves shown on the graph.

Thus, the time-dependent tidal strains associated with the satellite's orbital inclination are smaller than those that a spherical satellite would experience. Estimates of tidal dissipation rates suggest that tides raised in Triton by Neptune could have been responsible for damping its orbital eccentricity but would not have significantly affected its orbital inclination. Moreover, tides raised in Neptune by Triton are unlikely to have been important (*9*).

The rate of orbital evolution attributable to tidal dissipation depends on two parameters, the tidal Love number, k_2, and the tidal quality factor, Q. For $e << 1$, the most relevant evolution rate is that for e at fixed a which reads (*9*)

$$\frac{1}{e}\frac{de}{dt} = -\frac{21}{2}\frac{n}{\mu}\left(\frac{R}{a}\right)^5\frac{k_2}{Q} \quad (1)$$

For $1 - e << 1$, the appropriate evolution equation is that for a at fixed periapse distance $r_p = a(1 - e)$ which takes the form (*10, 11*)

$$\frac{1}{a}\frac{da}{dt} = -\frac{21}{64}\frac{n}{\mu}\frac{aR^5}{r_p^6}\frac{k_2}{Q} \quad (2)$$

The above equations, and plausible estimates of $k_2 \approx 0.1$ and $Q \approx 10^2$, imply that if Triton had been captured onto an orbit with $a \approx 10^3\ R_N$, tidal dissipation could account for its present orbit. Figure 1 shows $a(t)$ computed with our nominal parameters.

Tidal dissipation heated Triton's interior and large-scale melting commenced when $a \approx 100R_N$. Melting reduced the satellite's elastic rigidity thereby increasing the tidal strains, k_2, and the rate of tidal dissipation in the solid part of the satellite. Even if dissipation in the fluid interior were negligible, melting would have enhanced the overall rate of orbital evolution (*5, 12*).

The tides raised by Neptune in Triton dissipate the satellite's orbital energy while conserving its orbital angular momentum. If this were the entire story, it would follow that when Triton's orbit was very eccentric, its periapse distance, r_p, would have been just half of its present semimajor axis, or $r_p \approx 7R_N$. However, including solar perturbations modifies this picture.

The sun induces a harmonic oscillation of Triton's specific angular momentum with period equal to one half of Neptune's year and amplitude

$$\delta h = \frac{15}{8} n_N a^2 \quad (3)$$

When Triton's orbit was very large and eccentric, δh was a significant fraction of the mean specific angular momentum, $\bar{h} = na^2(1 - e^2)^{1/2} \approx 2^{1/2} n a^{3/2} r_p^{1/2}$. The corresponding solar perturbation of specific orbital energy was a negligible fraction of its mean. The behavior of the periapse distance follows from the relation $r_p \propto h^2$ that holds for $1 - e << 1$.

Acting together, the solar perturbations and the tides imposed secular variations on δh and $\bar{h}$. The limiting values of periapse distance as a function of a are depicted in Fig. 2. They converge toward a common curve as a, and hence the influence of the sun, decreases. The evolution of the minimum periapse, $\min(r_p)$, is more gradual than that of the maximum value, $\max(r_p)$, as a consequence of the short range of the tidal interaction.

Solar perturbations also complicated the evolution of Triton's orbital inclination. The precession of the satellite's orbit plane is forced by torques produced by the sun and by Neptune's oblateness. These torques are misaligned by Neptune's obliquity of 30°. Solar perturbations dominate for $a_T >> 100R_N$ and the planetary oblateness takes control for $a_T << 100R_N$. Following capture, Triton's orbital plane maintained nearly constant inclination to Neptune's orbital plane; currently, it maintains nearly constant inclination to Neptune's equatorial plane. We have not thoroughly investigated the transition from solar to planetary control of Triton's orbital inclination. Consequently, we pretend that Triton's orbit always maintained constant inclination to Neptune's equatorial plane. However, we properly account for the effect of solar perturbations on the precession rate. This procedure is equivalent to neglecting Neptune's obliquity.

Perturbations forced by Triton. Triton perturbs the orbits of Neptune's other satellites. At present, these perturbations are uninteresting. However, during the time Triton's orbit was eccentric, the perturbations it forced were more profound.

Triton crossed the orbit of Nereid about 10^8 times. During a typical crossing it produced perturbations of order $\mu \approx 3 \times 10^{-4}$ in $\Delta a/a$, e, and i of Nereid. Successive perturbations were essentially uncorrelated and thus produced a random walk in the values of each of these quantities. The number of crossings and the sizes of the individual perturbations are adequate to account for Nereid's irregular orbit.

Regular satellites with $a \gtrsim 5R_N$ must have suffered perturbations during even more numerous orbit crossings by Triton. Moreover, the probability of physical collisions with Triton must be accounted for. To estimate this, we approximate Triton's orbit by an inclined parabola with periapse distance r_p. The probability distribution for the distances at which Triton passed through Neptune's equatorial plane is given by

$$g(r) = \frac{2}{\pi r}\left(\frac{r_p}{r - r_p}\right)^{1/2} \quad (4)$$

where we have taken the arguments of periapse and node to be uniformly distributed because they are forced to precess by the sun and by Neptune's quadrupole moment. Note that $\int_{r_p}^{\infty} dr\, g(r) = 2$ since Triton passes through the equator plane twice each orbit. Multiplying $g(r)$ by $R_T^2/2r$, we obtain the probability per orbit that Triton would have collided with a satellite at radius r,

$$p(r) = \frac{1}{\pi}\left(\frac{R_T}{r}\right)^2\left(\frac{r_p}{r - r_p}\right)^{1/2} \quad (5)$$

The expression for $p(r)$ is invalid, and must be modified, within a few R_T of r_p. The probability that a satellite at distance r suffered a

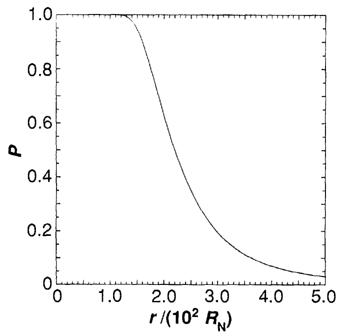


Fig. 3. Probability that Triton would have collided with a satellite moving on a circular orbit of radius r.

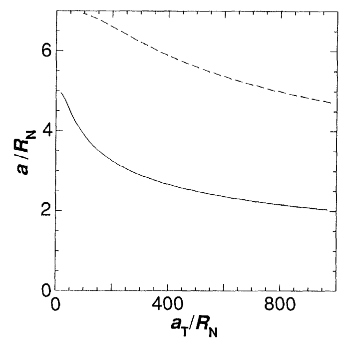


Fig. 4. The boundary separating regions of chaotic and integrable motion as a function of Triton's semimajor axis. The dashed line is for $r_p = 7R_N$ and $i_T = 0$. The solid line is for variable r_p as shown on Fig. 2 and $i_T = 40°$. The chaotic region is to the right of the boundary in each case.

collision with Triton is given by

$$P(r) = 1 - \exp[-Np(r)] \quad (6)$$

where N is the number of orbits Triton made before tidal dissipation caused its apoapse to shrink within r.

The plot of $P(r)$ displayed in Fig. 3 shows that $P(r)$ is essentially unity within $5R_N < r < 100R_N$. Since Triton would have cannibalized smaller satellites with which it collided, the absence of a regular satellite system around Neptune becomes understandable (*4, 13*).

Close to the planet, in the region where Triton never penetrated, regular satellites might still survive. If comparison with the satellite systems of other giant planets is an accurate guide, several satellites must have formed in this region. While Triton moved on a highly eccentric orbit, they would have suffered impulsive perturbations each time it passed periapse. The sizes of the dimensionless perturbations $\delta a/a$, δe, and δi are of order

$$\epsilon = \mu f(a/r_p) \quad (7)$$

where $f(z)$ is a dimensionless, monotonic, increasing function of z. The cumulative effects on the orbital elements depend upon whether these perturbations are integrable or chaotic. The former produce bounded periodic oscillations whereas the latter drive unbounded diffusive variations.

Successive perturbations, separated in time by the orbital period of Triton, P_T, may be used to define an area preserving map that bears a close relation to the standard map of nonlinear dynamics (*14*). We have carried out direct integrations of the equations of motion to verify that our map accurately simulates the particle dynamics. The map is characterized by a single parameter, K. If $K \gtrsim 1$ the trajectories are integrable, and if $K \lesssim 1$ they are chaotic. In our example,

$$K = \max(\delta n)P_T \approx \mu n P_T f(a/r_p) \quad (8)$$

The perturbations are chaotic provided they are able to change the test particle orbital phase at the next encounter, $\delta\phi = \delta n P_T$, by more than a radian.

The dashed line in Fig. 4 demarcates the region where Triton would have forced chaotic perturbations according to Eq. 8 with K calculated neglecting solar perturbations and assuming $i_T = 0$. This curve underestimates the extent of the region of chaotic perturbations for several reasons. Most importantly, solar perturbations force a periodic variation of r_p as shown in Fig. 2. This enlarges the chaotic region for two reasons. It lengthens the interval between the strongest perturbations beyond P_T and decreases the minimum r_p below $7R_N$. The inclination of Triton's orbit also increases K because, especially when Triton's periapse and node coincide, it decreases the cancellation between the angular momentum transferred to the test particle on opposite sides of its closest approach to Triton. Accounting for the effects of solar perturbations and Triton's orbital inclination shifts the boundary of the zone of chaotic perturbations inward as depicted by the solid curve in Fig. 4.

The map previously alluded to accounts for the periodic solar perturbations of Triton's periapse distance. It also includes the precessions of ϖ_T and Ω_T due to the sun and of ϖ and Ω due to Neptune's oblateness. A limitation is that it is strictly valid only for $e << 1$ and $i << 1$.

When our map is iterated holding a_T constant, the behavior of the orbital perturbations is about as expected. For $K \gtrsim 1$, a, e, and i exhibit chaotic variations. The variations of a are biased toward increasing values because K increases with a at fixed a_T; that is, the effective diffusion constant increases with a.

Qualitatively new features appear in the perturbations of each of the orbital elements when a_T is taken to decrease as shown in Fig. 1. As before, for $K \gtrsim 1$ there is a component of chaotic motion. However, more regular variations are also observed. Those in a arise from the temporary trapping of n in high order resonances with n_T as these resonances sweep inward past the satellite. Similarly, temporary resonances account for the jumps observed in e and i.

Our map also accounts for damping of the satellite's orbital eccentricity by tides raised in it by Neptune. Tidal damping makes attractors of the stable fixed points of the map. Thus it enhances the frequency and duration of temporary resonance capture. Moreover, tidal dissipation lowers orbital energy at constant angular momentum so that, accompanied by the chaotic driving of e by Triton, it leads to a secular decrease of a.

We present three examples of inner satellite orbital evolution in Figs. 5 to 7. They differ only in the initial value chosen for a. For the purpose of computing tidal damping the satellite's parameters were taken to be $R = 10^2$ km, $Q = 10^2$, and $k_2 = 5 \times 10^{-4}$. The effects of tidal dissipation are apparent only in the evolution of the outermost test particle. Each simulation involves 10^7 iterations of the map and covers the portion of Triton's orbital evolution during which a_T decreased from an assumed initial value of $10^3 R_N$ to about $6 \times 10^2 R_N$. These were the longest simulations we could afford.

Extrapolation to longer times suggests that a significant fraction of those satellites that once occupied orbits close to Neptune had their orbits perturbed until they were accreted by either Triton or Neptune. Moreover, those that escaped destruction must move on inclined orbits.

Neptune's arcs and satellite X. The existence of Neptune's ring arcs is deduced from a few confirmed stellar occultations. Geometrical considerations suggest that between 10 and 100 arcs orbit the planet (*3*).

Corotation resonances associated with a satellite are natural candidates for the azimuthal confinement of arc material. A satellite with a circular equatorial orbit has a pair of corotation resonances suitable for confining arcs; these are located at the equilateral triangular points, L_4 and L_5 (*15*). However, a large number of these satellites would be required to account for Neptune's numerous arcs. It is more economical to suppose that all of the arcs are confined by the corotation resonances of a single satellite, henceforth referred to as satellite X. This is possible provided the satellite's orbit has

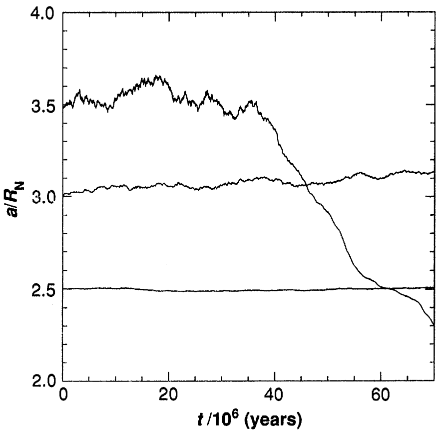


Fig. 5. The semimajor axis of an inner satellite as a function of time following the capture of Triton at $a_T = 10^3 R_N$ with $i_T = 40°$ for three different initial values of a. During the interval shown Triton made 10^7 periapse passages and its semimajor axis decreased to about $600R_N$.

Fig. 7. Same as for Fig. 6 but for i instead of e.

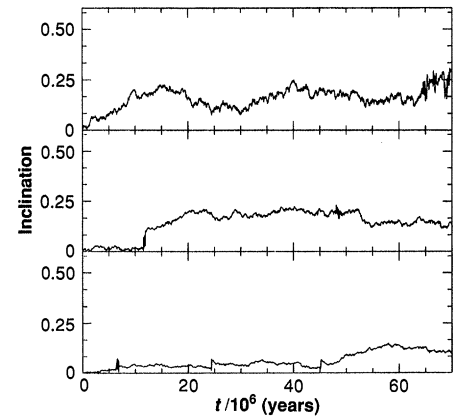
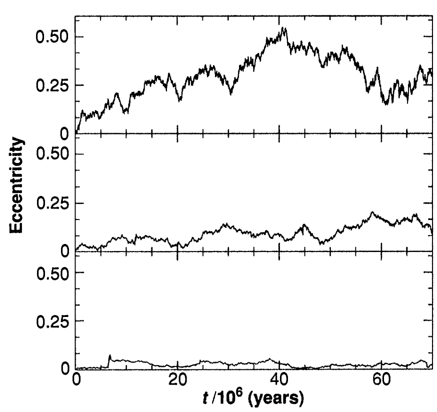


Fig. 6. Each panel shows the evolution of e corresponding to one of the trajectories of Fig. 5.



substantial eccentricity or inclination. In either case, there would be corotation resonances suitable for arc confinement at many different orbital radii (*16*).

We expect that tidal dissipation damped the orbital eccentricity of satellite X. Thus its orbit should share with that of Triton the unusual characteristic of being circular yet inclined. Moreover, satellite X owes its irregular orbit to perturbations produced by Triton. This is the link that connects Neptune's unique satellite system to its unique set of ring arcs.

Corotation resonances are locations of potential maxima so dissipation associated with particle collisions tends to cause arcs to spread. This tendency may be stymied by the input of energy due to Lindblad resonances (*15–17*). Remarkably, there is an appropriate Lindblad resonance associated with each corotation resonance of satellite X, except for those that share the satellite's semimajor axis, that is, L_4 and L_5 (*16*).

The maintenance of complete narrow rings requires the existence of at least two shepherd satellites (*18*). The absence of such rings around Neptune is consistent with the presence of a single dominant inner satellite.

The widths and lengths inferred for the arcs imply that $R_X \gtrsim 30/(\sin i)^{2/3}$ km. Thus it should be seen in images taken by Voyager 2 well before Neptune encounter. Indeed, there is some chance that it could be detected earlier by ground-based observations in the near infrared. Detection by stellar occultation is an improbable means of discovering Neptunian satellites because their disks subtend very small solid angles at Earth. However, a sizable, diameter $\gtrsim 90$ km, object apparently was detected in just this manner, so perhaps satellite X has already been found (*19*).

Capture by gas drag. Gas drag is often invoked as the dissipative mechanism responsible for the permanent capture of satellites, in particular, those that orbit far from their parent planets (*20*). We have shown that gas drag was not needed for the capture of Triton. Furthermore, it would be difficult to reconcile a significant role for gas drag with the survival of satellite X close to Neptune.

Triton as a regular satellite. Suppose Triton formed as a regular satellite of Neptune and had its orbit perturbed by a large planetesimal. Two possibilities come to mind.

Perhaps a planetesimal came very close to Triton and reversed the direction of its orbital motion. Alternately, Neptune's spin might have been retrograde when Triton formed and then had been reversed by the impact of a planetesimal. Both possibilities require a planetesimal of at least the mass of Earth. In either case, Triton would have been placed on an eccentric and inclined orbit and much of our discussion regarding its effects on other satellites would still be pertinent. The discovery of new satellites would test the hypothesis of spin reversal which implies that their orbits should be retrograde.

When account is taken of target areas and gravitational focusing by Neptune, it is found that an Earth-size planetesimal that penetrated within $15R_N$ would have a comparable probability, of order a few tenths of a percent, of reversing either the orbital angular momentum of Triton or the spin of Neptune (*21, 22*).

The small values of the orbital eccentricity and inclination of Neptune pose a problem for the above hypotheses. How could Neptune's orbit have ended up so regular if the planet had interacted with Earth-size planetesimals? This same problem arises in attributing the sizable obliquities of the giant planets to the accretion of large planetesimals (*23*). However, interactions of protoplanets with small planetesimals and gas may have acted to regularize the planets' orbits without damping their obliquities.

We have presented a speculative scenario for the origin of Neptune's satellite and ring systems, one that has the virtue of linking their unique features to the capture of Triton. The discovery of a sizable inner satellite moving on an inclined orbit would provide strong support for our story.

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"There's something wrong with the retrieval system."