Neptune's capture of its moon Triton in a binary-planet gravitational encounter

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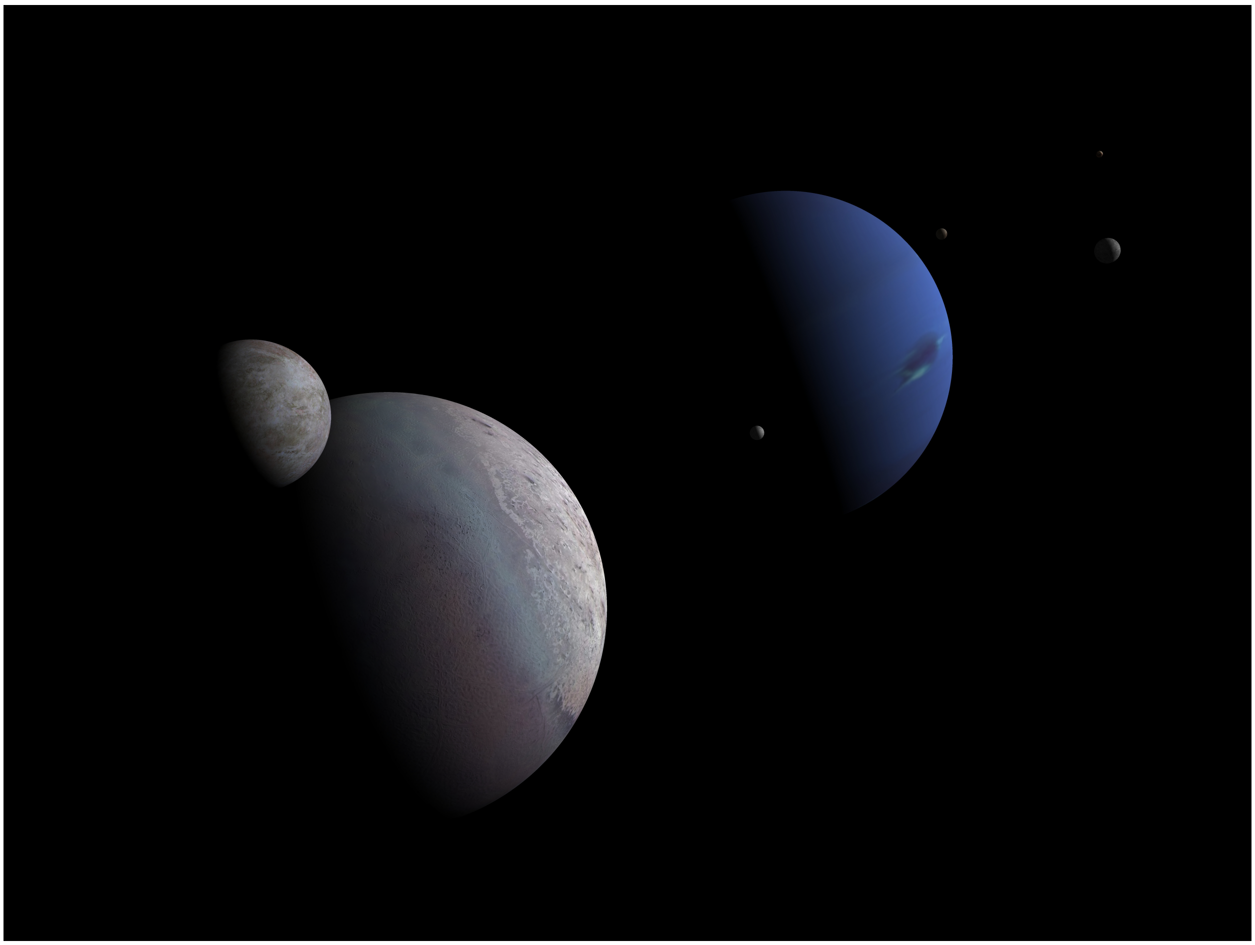

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COVER CAPTION

The cover image depicts Triton and its binary companion as they approach Neptune. As described in the Letter, this encounter facilitated Triton's capture to an inclined retrograde orbit about the planet; an event that catastrophically altered Neptune's satellite system. In the image Neptune is orbited by several primordial satellites that may have existed prior to the depicted encounter. These satellites would have been destroyed by mutual catastrophic collisions in the aftermath of Triton's capture to a large eccentric orbit. (©2006).

COVER ART ACKNOWLEDGEMENTS

We kindly thank Steve Albers (NOAA, CIRA) for creating and providing surface maps of Triton (based on Voyager 2 images) as well as those of several other planets and satellites. These surface maps are maintained as a part of NOAA's 'Science on a Sphere project' http://laps.noaa.gov/albers/sos/sos.html. We also thank James Hastings-Trew (for creating) and Constantine Thomas (for modifying) the surface map of Neptune (also based on images from the Voyager 2 flyby) and making it available. Finally, we thank Jerry Gardner for creating the artistic surface and texture maps used for Triton's companion.

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Triton is Neptune's principal satellite and is by far the largest retrograde satellite in the Solar system (its mass is ∼40 per cent greater than that of Pluto). Its inclined and circular orbit lies between a group of small inner prograde satellites and a number of exterior irregular satellites with both prograde and retrograde orbits. This unusual configuration has led to the belief that Triton originally orbited the Sun before being captured in orbit around Neptune[1–3]. Existing models for its capture[4–6] however, all have significant bottlenecks that make their effectiveness doubtful. Here we report that a three-body gravitational encounter between a binary (of $\sim 10^3$-kilometre-sized bodies) and Neptune is a far more likely explanation for Triton's capture. Our model predicts that Triton was once a member of a binary with a range of plausible characteristics, including ones similar to the Pluto/Charon pair.

One possible outcome of gravitational encounters between a binary and a planet is an exchange reaction, where one member of the binary is expelled and its place taken by the planet (Fig. 1). Analogous three-body encounters have been studied in a variety of contexts[7–10]; these studies suggest that the process may be relevant to the capture of planetary satellites[10] in general and for Triton[11] in particular. Here we develop an analytic description of this process and evaluate it using numerical simulations of binaries encountering Neptune. Satellite capture via this pathway requires that: i) the capture candidate be a member of a binary, ii) the binary be disrupted during the encounter, and iii) one of its members be left permanently bound to the planet.

Binaries have recently been discovered in nearly all of the solar system's small body reservoirs and appear to be a natural consequence of planet formation and solar system evolution[9,12–16] Recent surveys have found satellites orbiting ∼16% of near-Earth asteroids[17], ~ 2% of large main belt asteroids[18], and ∼11% of Kuiper belt objects[19], including Pluto and the recently discovered 2003 UB_{313}. Given the observational constraints, the true fraction of objects with satellites is likely larger and binary-planet encounters are therefore highly probable.

Three-body encounters will render the binary unbound when its centre of mass passes close enough to the planet that the binary separation is approximately its Hill sphere. This occurs at a tidal disruption distance of

$$r_{td} = a_B \left(\frac{3M_p}{m_1 + m_2} \right)^{1/3} = R_p \left(\frac{a_B}{R_1} \right) \left[\left(\frac{3\rho_p}{\rho_1} \right)^{1/3} \left(\frac{m_1}{m_1 + m_2} \right)^{1/3} \right] \tag{1}$$

from the planet, where a_B is the binary semi-major axis, M_p, R_p, and ρ_p are the planet mass, radius, and density, respectively, and $m_{1,2}$ and ρ_1 are the binary masses and density with $m_2 < m_1$. Since the term in square brackets is near unity, the disruption distance measured in planetary radii is nearly the binary's separation measured in radii of its largest component (R_1). Numerical simulations of binary-planet encounters confirm this as the effective scaling length for binary disruption. Results also show disruption to be a strong function of the inclination of the binary orbit relative to the encounter plane (I_B). Prograde binaries with $I_B < 90°$ are efficiently disrupted for close approach distances $q_e \lesssim r_{td}$, but retrograde ones ($I_B > 90°$) require much deeper encounters. Similar inclination dependence of disruption has been observed in several studies of tidal interactions[10,20,21].

Using the results of simulated binary-planet encounters as a guide we find that a simple model, which assumes the binary is impulsively disrupted, provides an effective description of the gravitationally focused encounters with Neptune considered here (Figs. 2 & 3). As the binary approaches the planet on a hyperbolic trajectory, m_1 and m_2 orbit their mutual centre of mass (Fig. 1). On disruption, the smaller body (m_2) experiences a change in speed of order its orbital speed about the binary centre of mass

$$\Delta v_2 \simeq \pm \frac{m_1}{(m_1 + m_2)} \left(\frac{G(m_1 + m_2)}{a_B} \right)^{1/2} \quad (2)$$

where G is the gravitational constant and $\Delta v_1 = \Delta v_2 \, m_2/m_1$. When combined with energy arguments, this change in speed allows the new semi-major axes to be determined (Fig. 3). Because the tidal forces that cause binary disruption are maximized when the three bodies are most nearly colinear, preferred binary orbital phases (and values of Δv_i near that of Eq. 2) are selected when disruption occurs. This results in a clustering of capture semi-major axes (a_c) around a characteristic value (see Fig. 3).

When the binary orbital angular momentum is much less than the encounter angular momentum, as in all cases considered here, the pericenter of the capture orbit (q_c) is comparable to that of the planet-centre of mass close approach distance (q_e) offset by the binary orbital separation, (i.e. $q_c \simeq q_e - a_B m_1/(m_1+m_2)$ for capture of m_2 with $I_B < 90°$ - Fig. 1). Since the inclination of the capture orbit is nearly that of the centre-of-mass trajectory about the planet, capture to prograde or retrograde orbits about Neptune is determined by this path. In principle, this mechanism can transfer an object to virtually any satellite orbit if the requirements of disruption and capture can be satisfied by the encounter dynamics (q_e, v_∞, I_B) and the binary characteristics ($m_{1,2}$, a_B). In practice, highly elliptical capture orbits are favored. We are examining the role of three-body encounters in the capture and evolution of additional relevant populations; a report is forthcoming.

The capture of Triton must transfer it to an orbit contained within Neptune's Hill sphere ($r_H = a_N(M_N/3M_\odot)^{1/3}$ where M_N, a_N are Neptune's mass and semi-major axis and $M_\odot$ is the solar mass) and the semi-major axis of the capture orbit is limited to values $a_c < r_H/2 = 2300R_N$. This large eccentric orbit may have intersected and/or strongly perturbed regions where Triton's neighboring satellites now reside, driving catastrophic collisions between primordial regular satellites and/or exciting the orbits of irregular satellites via close encounters and secular interactions[1,6,22,23]. Following capture, Triton's orbital semi-major axis and eccentricity decayed to the currently observed $a_T = 14.06R_N$ and $e_T = 4\times10^{-4}$) owing to satellite tides[1,24] and accumulation of collisional debris[22]. Tides alone cause the orbit to damp while maintaining constant angular momentum, suggesting that the pericenter of Triton's eccentric capture orbit was near $q_c \sim a_T/2$. Capture to this q_c requires close passage to Neptune with $q_e \lesssim 7R_N$ and binary separations and masses such that $q_e \lesssim r_{td}$. We note that for large capture orbits (e.g. $a_c \gtrsim 200R_N$) solar and secular perturbations can drive substantial oscillations in Triton's orbital angular momentum[6,22,23,25], expanding the range of plausible capture pericenters considerably.

Using these constraints we show that Triton's capture can be facilitated by binaries with a wide range of characteristics (Fig. 4). The semi-major axes must satisfy $(a_B/R_1) \gtrsim 5$ for efficient disruption, so that $r_{td} > 7R_N$, and Triton's companion must be sufficiently massive to provide the required impulse. In practice this is not particularly restrictive and the escaping object can actually be less massive than Triton. For small values of v_∞ and large capture orbits a_c, the escaping companion may be as small as a $few \times 0.01m_T$.

Previous models for Triton's capture invoke aerodynamic drag in a protosatellite gas disk[5] or collision with a pre-existing regular satellite of Neptune[6]. For aerodynamic drag, capture must be carefully timed, occurring during the lifetime of the protosatellite gas disk–of order $10^3 - 10^6$ yr (ref. 3)–and just prior to the disk's dispersal to avoid continued orbital decay into the planet. Collision capture requires an extremely unlikely event. The probability of colliding with a single regular satellite given one encounter with $q_e < 10R_N$ is low ($P_c \sim (R_T)^2/(10R_N)^2 \sim 3 \times 10^{-5}$ where R_T is Triton's radius) requiring numerous $(\gtrsim 10^3)$ close passes with Neptune to make the occurrence of a single collision reasonable. Also, the impacting satellite must be large enough to capture, but not so large $(\gtrsim 0.01m_T)$ as to catastrophically disrupt Triton[3,26]. A review of these models[3] slightly favors collisional capture. Clearly, both mechanisms require specialized conditions, ones primarily available during Neptune's formation, to function.

Gravitational capture of one binary component offers a number of significant advantages. As with previous models, capture can be realized for conditions prevalent during Neptune's formation. However, capture might also occur later as encounters between Neptune and material from an exterior planetesimal disk drove the planet's outward migration[27,28]. Further, exchange capture is gentle and brief for Triton and does not concomitantly subject it to loss via collisional disruption or continued orbital decay. Depending on the binary characteristics, Triton may be captured to a wide range of satellite orbits, including those tightly bound to Neptune ($a_c \lesssim 100R_N$, e.g. Fig. 1), making binary exchange capture consonant with many different plausible orbital histories for Triton and evolutionary paths of the Neptune satellite system.

Consider a single binary of the right type (Fig. 4) approaching Neptune with $q_e < r_{td}$. Assuming an isotropic distribution of binary orientations (I_B), 25% will have encounters with $I_B \leq 60°$, and will be efficiently disrupted and captured. Noting the additional 50% chance of securing Triton from the binary, the odds that this single binary-Neptune encounter will result in Triton's capture are at least 1/8.

Exchange capture is favored over collision capture if the probability that Triton once resided in a favorable binary exceeds $\sim 8P_c \sim 3 \times 10^{-4}$ (assuming similar capture cross-sections, i.e. $q_e \leq 10R_N$). Given the observed 11% lower limit on the frequency of KBO binaries[19] and the weak constraints on the binary characteristics required, we find exchange capture much more likely than collision[6]. We conclude that Triton was once a member of a binary and was captured as it made a close approach to Neptune.

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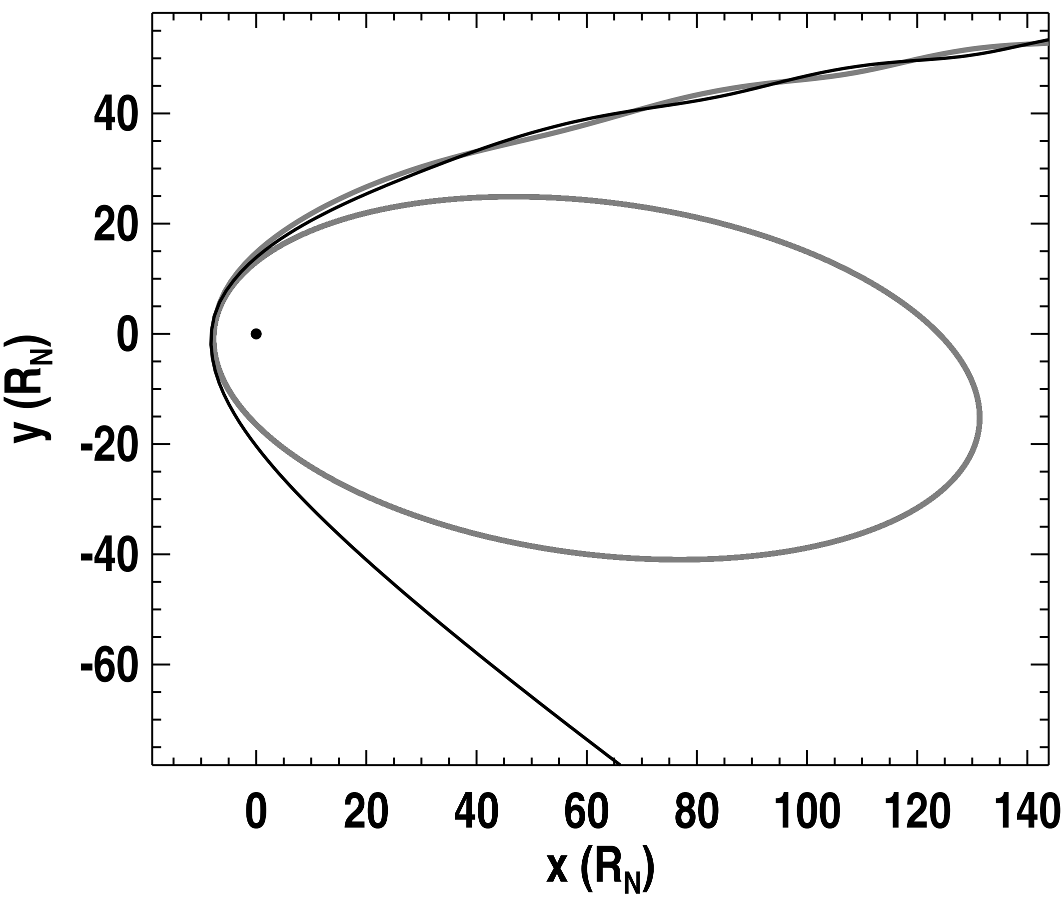
Figure 1 **Exchange capture of Triton.** We show trajectories of an example encounter in arbitrary planetocentric cartesian coordinates between an equal-mass Triton binary ($m_1 = m_2 = m_T$, where m_T is Triton's mass) and Neptune . The encounter is planar ($I_B = 0$) with encounter speed at infinity $v_\infty = 0.50$ km/s and close approach distance $q_e = 8R_N$. The initial binary orbit is circular ($e_B = 0.0$) with semi-major axis $a_B = 20R_1 \simeq 1.1R_N$, where R_1 is the radius of the larger component, R_N is Neptune's radius, and we have assumed a density of $\rho_1 = 2.0$ g cm^{-3} (similar to Triton). The binary approaches from the upper right and is disrupted while interior to $\sim r_{td} = 21R_N$ from Neptune. One member is captured to an orbit with semi-major axis $a_c \simeq 70R_N$ while the other escapes. We used a Bulirsch-Stoer integrator to model binary-planet gravitational encounters. For a given set of encounter dynamics (v_∞, q_e) and binary characteristics ($m_{1,2}, a_B, e_B, I_B$), we performed hundreds of simulations with different initial binary orbital phases.

Figure 2 **Outcomes of simulated binary-planet encounters.** Simulation results of a Triton binary ($m_1 = m_T$, $m_2 = 0.1m_T$, $a_B = 20R_1$, $e_B = 0.0$) encountering Neptune at speeds $0 < v_\infty < 2.0$ km/s are shown above. Larger values are unlikely, as Neptune's orbital speed is only $v_N = 5.4$ km/s, and crossing orbits have relative speeds $v_\infty \approx e_\odot v_N$, where $e_\odot$ is the heliocentric eccentricity. In all cases, $I_B = 0°$ and the binary centre-of-mass close approach distance is $q_e = 8R_N$. The encounters are deep within the binary tidal radius ($r_{td} = 26R_N$), and permanent disruption occurs in ~95% of cases (the dashed black line). As the binary tumbles towards the planet, each component spends half its orbit moving faster and half slower than the binary CM. The more massive object (m_1)

moves with a smaller, but non-negligible velocity relative to the centre of mass (see Eq. 2). For $v_\infty \lesssim 0.35$ km/s either binary is captured with roughly 50% probability due to orbital phasing at the time of disruption. At higher velocity ($0.35 < v_\infty \lesssim 1.55$ km/s) capture of m_1 is possible, but rare while m_2 is still captured at a 50% rate due to its greater orbital speed in the binary centre-of-mass frame.

Figure 3 Determining capture orbits. For the simulations in Fig. 2, we show the range of orbital semi-major axes of the capture orbits (a_c) as a function of the encounter speed (v_∞). Thin vertical lines connect the minimum and maximum values of the capture semi-major axis (a_c) for the larger ($m_1 = m_T$; grey) and smaller ($m_2 = 0.1m_T$; black) binary components observed in our simulations. We have omitted these lines for encounters where less than 5% of simulations resulted in capture. Thicker lines denote the range where 50% of the capture orbits lie and indicate that the distribution of semi-major axes is clustered toward a characteristic value for each encounter velocity. When $M_p \gg m_{1,2}$ impulsive transfer from a hyperbolic encounter orbit with approach speed v_∞ to a bound elliptical orbit with semi-major axis a_c at a distance r from the planet requires a reduction in speed of $\Delta v_c = \sqrt{v_\infty^2 + 2GM_p/r} - \sqrt{GM_p\,(2/r - 1/a_c)}$. Equating $\Delta v_c = \Delta v_2$ from Eq. (2) yields an expression relating the binary characteristics to the encounter and capture orbits. Overplotted curves show the values of a_c predicted assuming a characteristic reduction in speed from Eq. (2) occurs at distances of $r = 0.6, 0.8,$ and $1.0r_{td}$ from the planet, with $r = 0.8r_{td}$ providing a good fit to the median a_c. For other binary characteristics and encounter dynamics we usually find good fits in the range $r = 0.6 - 0.8r_{td}$. Results for modestly inclined ($I_B \lesssim 60^{\circ}$) and/or eccentric binaries are qualitatively similar.

Figure 4 Binaries capable of delivering Triton to Neptune. Efficient binary disruption requires $q_e < r_{td}$; using Eqs. (1)-(2), and assuming that the change in speed occurs near $r = 0.8r_{td}$, we solve for the mass of the escaping companion. We show the masses required for capture with $a_c \leq 2300R_N$ (black) and with $a_c = 200R_N$ (grey) as a function of a_B/R_1. These curves were generated by inverting fits to the median values in Fig. (3), and are representative of a range of the binary parameters needed to transition Triton between encounters with speed v_∞ and capture orbits of size a_c. Scenarios of Neptune's accumulation[26,29,30] give encounter speeds $v_\infty < 0.5$ km/s or $e_\odot < 0.1$. Delivery to small semi-major axes is possible (e.g. Fig. 1) and becomes more probable with more massive companions. Binaries facilitating Triton's capture have properties similar to those of known Kuiper Belt binaries (i.e. $m_2/m_1 \simeq 0.05 - 1$, $a_B/R_1 \simeq 17 - 1300$)[18] and to the Pluto/Charon pair ($m_{Charon}/m_{Pluto} = 1/8$ and $a_B/R_{Pluto} \simeq 17$) in particular.



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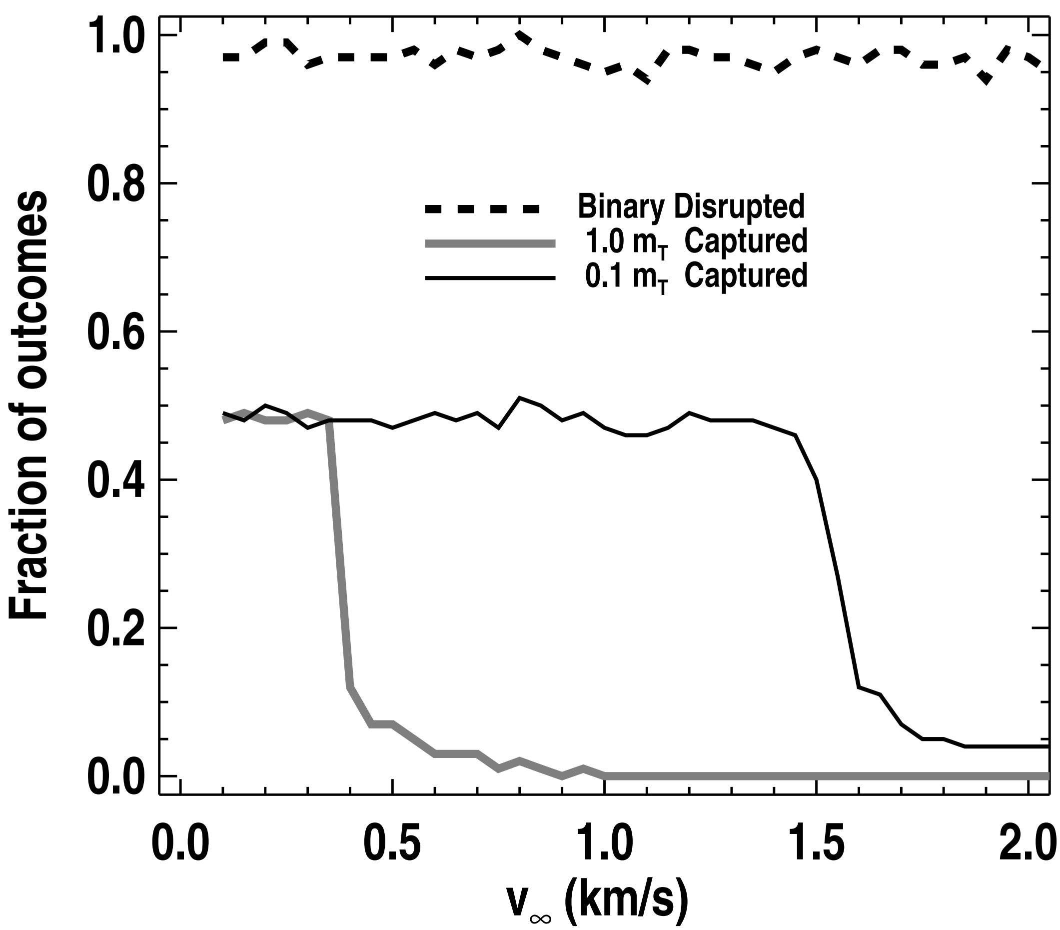


Binary Disrupted
1.0 m_T Captured
0.1 m_T Captured
Fraction of outcomes
v_∞ (km/s)
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.5
1.0
1.5
2.0

Fig. 2.—

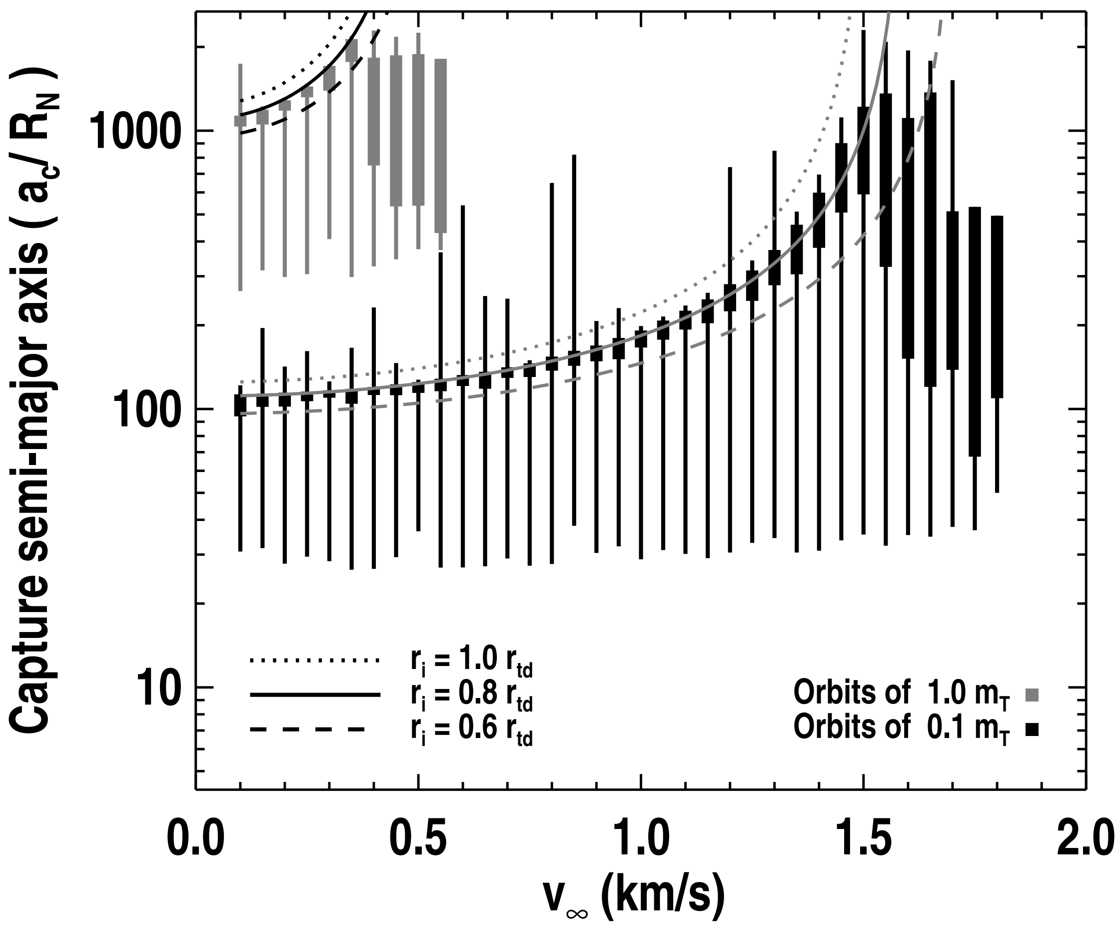
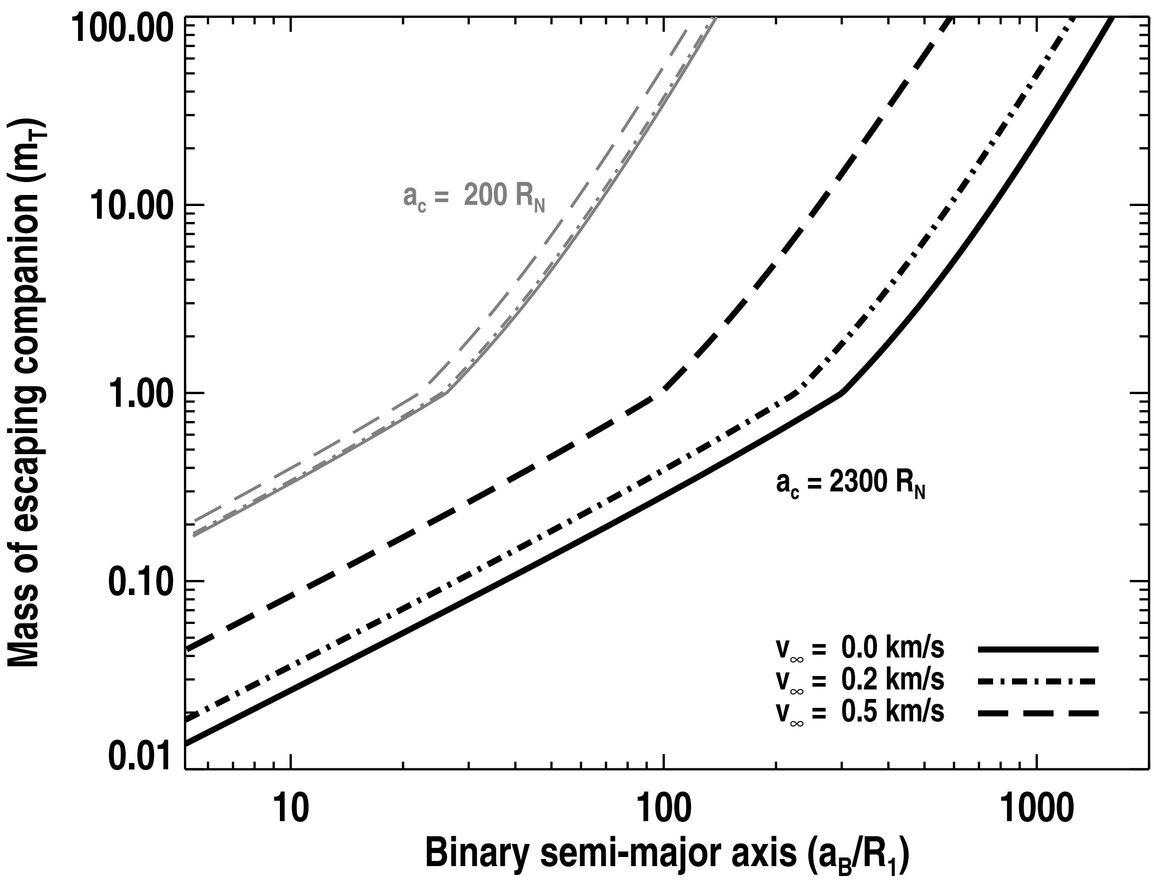

Capture semi-major axis (a_c/ R_N)
1000
100
10
0.0
0.5
1.0
1.5
2.0
v_∞ (km/s)
r_i = 1.0 r_td
r_i = 0.8 r_td
r_i = 0.6 r_td
Orbits of 1.0 m_T
Orbits of 0.1 m_T

Fig. 3.—



100.00
10.00
1.00
0.10
0.01
10
100
1000
Mass of escaping companion (m_T)
Binary semi-major axis (a_B/R_1)
a_c = 200 R_N
a_c = 2300 R_N
v_∞ = 0.0 km/s
v_∞ = 0.2 km/s
v_∞ = 0.5 km/s

Fig. 4.—