INTRODUCTION. A secondary body which passes close to a primary body is subject to tidal forces strong enough to result in tidal disruption if the secondary body remains on a circular (or elliptical) orbit within a certain radius of the primary. This radius, termed the Roche limit, is determined by the densities of the two bodies and the radius of the primary:

\[ r_R = 2.5R\bigg(\frac{\rho'}{\rho}\bigg)^{1/3}, \]

where primes refer to the primary body. When a secondary body passes within the Roche limit of a primary while on a parabolic or hyperbolic trajectory, the applicability of the Roche limit is uncertain, because tidal forces can only operate during the finite time provided by the close encounter. Numerical attempts to quantify the effects of tidal disruption during close encounters have led to disparate results in the past [1,2], but recently a coupled analytical and numerical study [3,4] appears to have improved the modeling of the physics of tidal disruption sufficiently to yield a general limit for disruption during close encounters. In the limit of very small secondaries, this general limit is

\[ r_p \approx R\bigg(\frac{\rho'}{\rho}\bigg)^{1/3}, \]

where \( r_p \) is the perigee radius, similar to the Roche limit but without the factor of 2.5, meaning that tidal disruption during a flyby requires much smaller orbital radii than in the Roche case.

TIDAL DISRUPTION LIMITS. A simple model [3,4] based on requiring the velocity dispersion generated by tidal forces to exceed the escape velocity of the secondary leads to a criterion for tidal disruption of a secondary into two hemispheres:

\[ \left(1 - \frac{R\cos\theta}{r_p}\right)^{-1/2} - 1 > \left(\frac{M}{8M'}\right)^{1/2} \left(\frac{r_p}{R}\right)^{1/2}, \]

where \( R \) is the secondary's radius, \( M \) is the secondary's mass, and \( \theta \) is the angle between the long axis of the secondary and the direction toward the center of the primary. In the limit of a very small secondary, and for \( \theta = 45^\circ \) (a typical phase angle found in the numerical models), equation (3) reduces to the form given in equation (2) above. Equation (3) is the most permissive of tidal disruption of the three criteria presented in [3,4]; these criteria were derived assuming parabolic orbits, which also errs on the side of encouraging tidal disruption. The criteria apply to inviscid bodies without dissipation or appreciable material strength; strongly dissipative (viscous) bodies are even more resistant to tidal disruption [5,6]. Hence the above limit should be a firm upper bound on perigees resulting in tidal disruption.

The analytical approach has been confirmed through numerical (SPH) calculations [3,4] of tidal encounters, using bodies with iron cores, silicate mantles, and realistic (dunite) equations of state. (SPH calculations have also been used recently to study tidal distortions accompanying collisions between bodies with polytropic equations of state [7].) The numerical models agree with the analytical result (see figures) that tidal disruption of relatively massive bodies (\( M > 0.1M' \)) cannot occur, even at grazing incidence and for parabolic orbits \((v_\infty = 0)\). The self-gravity of massive bodies prevents their disruption. Tidal disruption is only possible for low mass \((M \sim 0.01M')\) bodies, and even then only for perigees close to grazing incidence and for mildly hyperbolic orbits \((v_\infty < 2 \text{ km s}^{-1} \text{ for an Earth-mass primary})\).
TIDAL DISRUPTION: Boss, A.P.

Equation (2) shows that in the limit of small bodies, tidal disruption can only occur when the density of the secondary is significantly less than that of the primary; otherwise, the perigee required for disruption falls within the primary and a collision would result instead. Using the more general criterion (3), the figures below demonstrate how the ratio $\rho/\rho'$ affects the possibility of tidal disruption for small bodies.

Figure Caption. Tidal disruption criterion (3) plotted for an Earth-mass primary (left) and a Uranus-mass primary (right). Short-dashed line is the Roche limit (1), solid line is criterion (3), long-dashed line is the locus of bodies with $\rho/\rho' = 1$ at grazing incidence, and the dotted line is the locus with $\rho/\rho' = 0.5$. Absolute stability to tidal disruption occurs for points to the left of the solid line (3). A cross-over occurs around $M/M' \approx 0.035$ for $\rho/\rho' = 0.5$; evidently bodies less massive than 0.035 $M'$ when $\rho/\rho' = 0.5$ may be tidally disrupted. Bodies with the properties of the Moon and Titan are shown at grazing incidence for Earth and Uranus, respectively. While Moon-like bodies could be disrupted by the Earth, Titan-like bodies (with $\rho/\rho' > 1$) are stable to disruption by Uranus-like primaries.

IMPLICATIONS. Small, inviscid bodies may only be tidally disrupted if their density is less than that of the primary and if their mass is less than a value determined by the ratio $\rho/\rho'$. Because of the prevalence of icy rheologies in the outer solar system and the lower temperatures required for melting, this inviscid tidal disruption limit is particularly applicable to outer solar system bodies.

Tidal disruption of a Chiron-like body by Saturn has been suggested as a means of replenishing Saturn's rings [8], but limit (2) implies that a Chiron ($\rho \sim 1$ g cm$^{-3}$) cannot be tidally disrupted by Saturn ($\rho' = 0.70$ g cm$^{-3}$).

Planetary accumulation in the outer solar system is thought to involve accumulation of $\sim 15$ Earth-mass (i.e., Uranus-mass) ice-rock cores [9,10]. During this process, only planetesimals with a mean density considerably less than that of the ice-rock cores are likely to be at all susceptible to tidal disruption.