THE TIDAL EVOLUTION OF STRENGTHLESS PLANETESIMALS: Erik Asphaug (NASA Ames Research Center 245-3, Moffett Field CA 94035, asphaug@cosmic.arc.nasa.gov) and Willy Benz (Steward Observatory, University of Arizona, Tucson AZ 85721)

When an interloper nears a planet, self-gravity and strength compete with tides in a dynamical manner which is difficult to resolve analytically. To break into ~21 pieces, Shoemaker-Levy 9 must have begun fracturing at $3.3R_J$, implying a maximum tensile strength[1] $\sigma_o \approx 40\,\mu$bars, about one ten-millionth the strength of rock. For this reason we ignore cohesion and use an N-body code with self-gravity and collisions[2] to study breakup scenarios constraining the parent comet's diameter and density and the masses of the bolides. The "string of pearls" was the result of self-gravitational instability[3] in a ~1.5 km diameter parent body of density $\rho_{bulk} \approx 0.6 \pm 0.1\,\mathrm{g/cm^3}$ elongated into a tube by tidal strain. The total mass of the parent comet was of order 10^{15} g.

Naturally, a spherical, strengthless and frictionless comet is an ideal representation. Because the impacts on Jupiter were so visually stunning, we explore some mechanisms that could allow for larger bolides. A somewhat larger comet is possible if the debris were fine-grained, but a large fraction of the mass would then be spread to the "wings". This would presumably cause large-scale atmospheric effects which were not observed. Delaying the onset of tidal strain until periapse (to account for maximum possible friction) also leads to a somewhat larger parent. In order to produce a chain of fragments resembling SL9, however, the bulk density must be lower ($\sim 0.3\,\mathrm{g/cm^3}$) so the total mass remains about the same. Retrograde rotation also makes a larger comet possible, but only at the expense of producing a dominant central clump which was not observed. Unless one invokes serendipitous factors (such as a prolate shape extending out of the orbital plane), a comet more massive than a few $\times 10^{15}$ g does not accord with any known physics of tidal disruption. This is a very typical object; for comparison, a 10^{15} g comet is 2/3 the estimated median size[4] of the parent bodies which have split to produce crater chains on Ganymede and Callisto.

Our code reproduces Sridhar and Tremaine's formal derivations[5] for the disruption threshold and fragment chain length of strengthless bodies on parabolic orbits. This work shows that SL9 could not have been an asteroid (**Fig. 1**). The periapse distance along a parabolic orbit at which a body *begins* to shed mass is $R_{min} = 0.69R_{roche}$, corresponding to a density $\rho_{max} = 2.8\,\mathrm{g/cm^3}$. To come apart into many pieces, the density must have been considerably lower. We expand our study to consider strengthless bolides of all sizes and densities, encountering planets of any mass along any parabolic trajectory, scaling our results in terms of the normalized impact parameter $b = R_{min}/R_{roche}$ (**Fig. 2**). Thus, to shed mass, $b < 0.69$. More than half a strengthless body's mass is lost when $b < 0.5$. (This "disruption annulus" is typically larger than the collisional cross-section of the planet, implying that near-misses can be fundamentally important in the evolution of small bodies.) Closer encounters ($b \sim 0.4$) produce debris chains resembling SL9, and low-density bodies grazing terrestrial planets suffer tides so strong ($b < 0.2$) that they are dispersed into constituent grains. The great excess of small near-earth objects could be the recent result of such an encounter.

Fig. 1 These analytical curves and numerical results depict the outcomes for the tidal disruption of strengthless bodies in parabolic orbits about Jupiter. (SL9's final orbit had eccentricity $e \approx 0.996$.) The Roche limit shows the periapse distance at which a liquid moon of density ρ in circular orbit can conform to no equipotential figure. The dark line is the disruption threshold of Sridhar and Tremaine[5] for parabolic orbits. Our numerical results for threshold disruption fall very close to this curve (Fig. 2g,h). The dark points mark the periapse at which the largest cluster contains half the total mass (Fig. 2d). The light points mark the periapse of SL9-type events, where the largest fragment contains 1/5 the total mass (Fig. 2c). For a periapse of $1.3R_J$, a strengthless asteroid with $\rho = 2.8\,\mathrm{g/cm^3}$ would have shed no mass whatsoever. To suffer SL9-type disruption an asteroid would have needed an impossibly small periapse $R_{min} \approx 0.7R_J$.

Fig. 2 The final orbital-plane positions (at $15R_{roche}$) of grains from planetesimals which have swung past a planet on various parabolic orbits. The scale is in planetesimal radii. The numbers $b = 0.12, 0.25, 0.40, 0.50, 0.55, 0.60, 0.65, 0.70$ and 0.80 refer to the scaled periapse distance $b = R_{min}/R_{roche}$ for each run. We have computed 600 such runs; these plots are independent of planetesimal size and density and planet mass.

REFERENCES: [1] Dobrovolskis, A.R., *Icarus* **88**, 1990. [2] Asphaug, E. and Benz, W., *Nature* **370**, 1994. [3] Chandrasekhar, *Hydrodynamic and Hydromagnetic Stability*, 1961. [4] Schenk, P. *et al.*, *LPSC XXVI* (this volume), 1995. [5] Sridhar, S. and Tremaine, S., *Icarus* **95**, 1992.

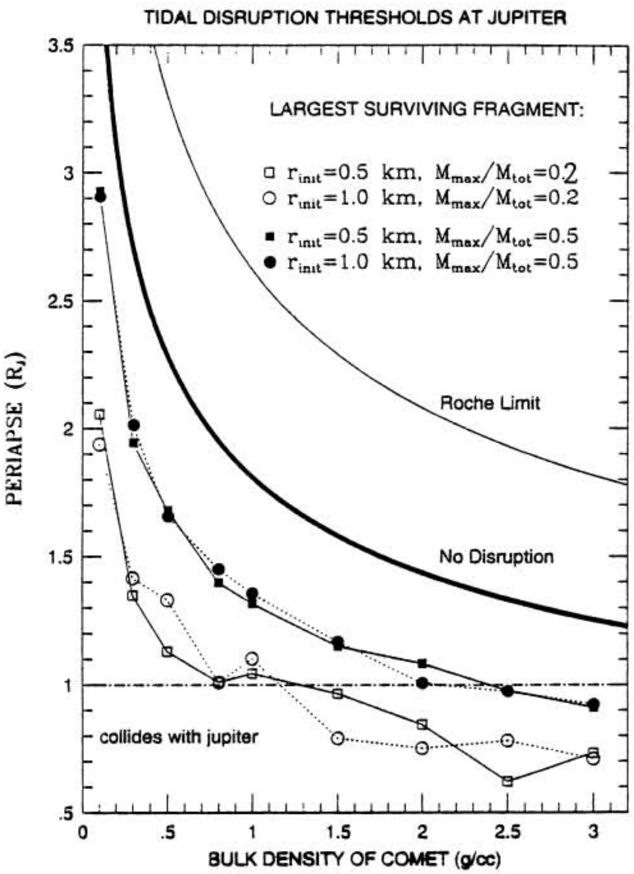

Figure 1

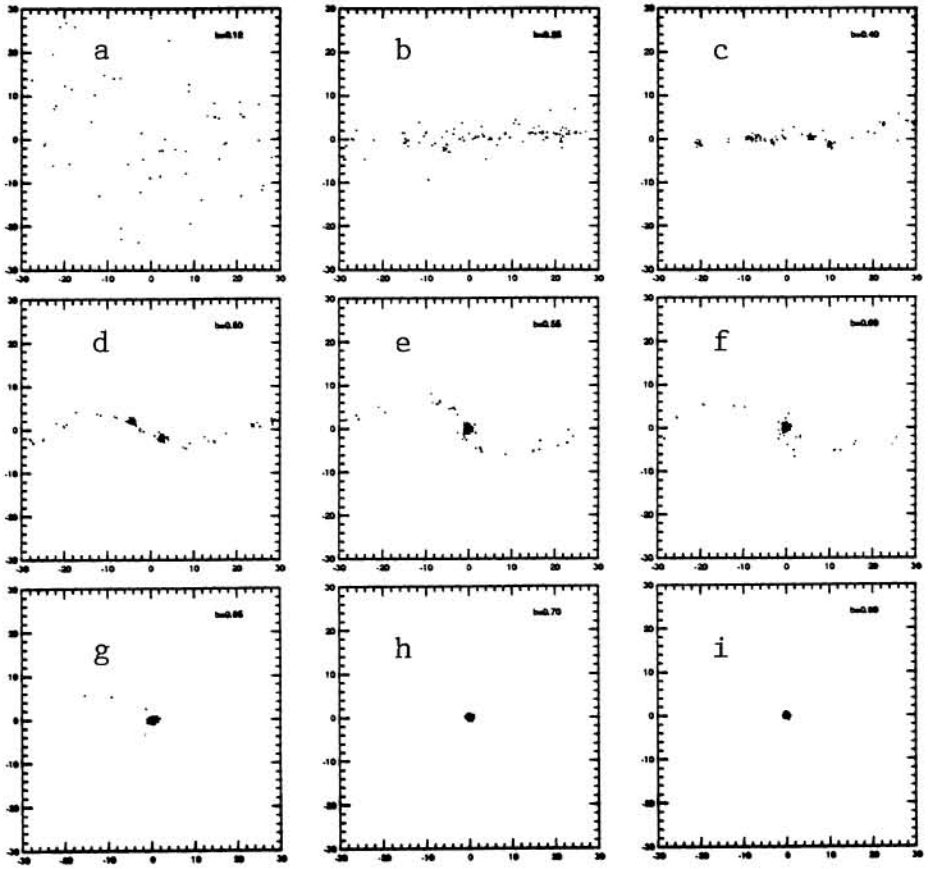

Figure 2