**THE PHYSICS OF GRANULAR FLOW AND THE TIDAL DISRUPTION OF COMET SHOEMAKER-LEVY 9** Naor Movshovitz and Erik Asphaug, Department of Earth and Planetary Sciences, University of California, Santa Cruz CA 95064, nmovshov@ucsc.edu, easphaug@ucsc.edu

**Introduction:** Most kilometer-sized asteroids are likely rubble-piles. Many comets may also be strengthless or nearly strengthless bodies, their fragility demonstrated when they break up far from perihelion for no obvious reason. One comet was observed shortly after it broke up for a very obvious reason: Comet Shoemaker-Levy 9 (SL9) made a spectacular plunge into Jupiter following a close approach two years previously, that disrupted the original progenitor into at least 21 detectable pieces. Tidal disruption by Jupiter is not unusual in the lives of short-period comets, as evidenced by numerous crater chains on Ganemede and Callisto, but having a detailed history of this one comet's fateful orbit we can infer something about the uncertain physical properties of comets.

A number of researchers have performed simulations of the SL9 tidal disruption with the hope of constraining the progenitor's size, bulk density, strength, shape, and spin state. For initial conclusions about SL9 see [1-4] and for a more general study of tidal disruption of rubble-piles see [6]. In [3,4], Asphaug and Benz explored in some detail the strength parameter, and concluded that the only way a comet on a nearly parabolic orbit with a perijove of 1.31 Jupiter radii can be broken up so thoroughly is if it were virtually strengthless, even in comparison with the minuscule tidal forces and its own self gravity. While the primary conclusion of their analysis was that SL9 and the split comets forming catenae craters on Ganymede and Callisto were rubble piles, they were also able to constrain the progenitor's bulk density with an upper limit of ~0.7 g/cm$^3$ in the limit of no friction. If the specific density of cometary materials is ~1.65 g/cm$^3$ [5] then this means a porosity of 60% or greater. This porosity has been attributed to microscopic voids (e.g., snow); macroscopic agglomerations (rubble piles), or fractal-like combinations.

**Methods:** Any numerical simulation of tidal disruption of complex aggregate solids under these very low stresses must make certain simplifications. Numerical aggregate models using spheres are the simplest and most computationally efficient. Asphaug and Benz [3,4] used up to 2000 uniform, frictionless spheres, described by mass, radius, and a softened restitutive potential. With advances in computing power a trend is emerging of applying models and methods of granular dynamics to the rubble-pile environment, paying more attention to accurate modeling of the individual grain constituents, including the effects of friction and non-spherical shapes. For examples of these methods see [7-10]. The adoption of assemblages of polyhedra [10] is required to obtain realistic angles of repose of a static pile, and leads to grain bridging, dilatation and shear localization which may be influential in the tidal disruption of rubble piles. We employ a new Discrete Element Model (DEM) based on a commercial physics engine [11] to revisit the SL9 event. Our code uses randomly generated shapes instead of spheres for the individual grains, simulating as many as 10,000 rigid bodies with arbitrary shapes, and individual coefficients of friction and restitution. Cohesion is supported but has not yet been tested in this application at the time of writing.

**Preliminary Results:** The inclusion of coefficient of restitution and intergranular friction, and irregular granule shape, creates a larger parameter space that we have begun to explore, with initial results for the bulk properties of comets.

We find that non-spherical grain shape has an important effect on the overall behavior of a rubble pile undergoing tidal shear, by introducing the effects of grain locking, dilatation and localization. **Fig. 1** and **Fig. 2** show the effects of identical tidal encounters on identical progenitor bodies, simulated as spherical grains (a) and as randomly generated polyhedra (b). The spheres-based body has the dynamics of an incompressible fluid, starting to clump later in its orbit (due to gravitational instability) than the polyhedra-based body which begins forming aggregates by grain locking. The spheres-based body ends up with one central clump and numerous small clumps, while the polyhedra-based body has a small number of more massive clumps.

We also model spheres-based bodies with and without friction, and find that the inclusion of friction can significantly delay the disruption of a rubble-pile body and alter the process of deformation. In **Fig. 3** the results of identical tidal events on identical progenitor bodies are shown, using (a) no inter-granular friction and (b) a friction coefficient of 0.2. Friction delays the onset of disruption and thereafter enhances clumping by increasing the stress threshold for deformation.

Using spheres-based bodies with friction we simulated a ~1 km radius body following the 1992 orbit of SL9. In all simulations the grains were given a coefficient of friction of 0.5 and a coefficient of restitution of 0.8 [12]. Including friction, a bulk density 0.5 g/cm$^3$ is too high for break-up into a dozen or more equal mass clumps. Our initial conclusion is that the estimate of comet density based on frictionless spheres [3,4] may be too high, and we obtain good fits using $\rho$~0.3-0.5 g/cm$^3$.

**Discussion:** Comets may be rubble piles, but they are probably not collections of polyhedra. What we present here is a model that introduces several important aspects of granular physics: friction, restitution, grain locking, and dilatation. Asteroids are also tidally disrupted by Earth before impacting the Moon, and the Lunar Reconnaissance Orbiter has already observed one relatively fresh crater chain (V. Bray, pers. comm.) caused by the disruption of an Itokawa-sized (~300 m) asteroid. These 'x rays' of rubble pile comets and asteroids are the best data, short of a seismic or radar imaging experiment, to reveal the internal structures of small bodies. Movies and images of our results in progress can be found at http://es.ucsc.edu/~nmovshov/comets.

**References:** [1] Sridhar S. and Tremaine S. (1991) *Icarus, 95,* 86–99. [2] Sekanina Z. et al. (1994). *Astron. Astrophys., 289,* 607-636. [3] Asphaug E. and Benz W. *Nature* 370, 120-124. [4] Asphaug E. and Benz W. (1996) *Icarus,* 121 225–248. [5] Greenberg et al. 1998. [6] Richardson et al. (1998) *Icarus* 134, 47-76. [7] Richardson et al. (2010) *DPS.* [8] Sanchez P. and Scheers D. J. (2010) *DPS.* [9] Tanga et al. (2009) *ApJ Letters*, 706, 1, L197-L202 [10] Korycansky D. and Asphaug E., *Icarus* 204, 316-329 (2009). [11] www.developer.nvidia.com/physx.html [12] Durda et al. (2010) *Icarus*, DOI:10.1016/j.icarus.2010.09.003

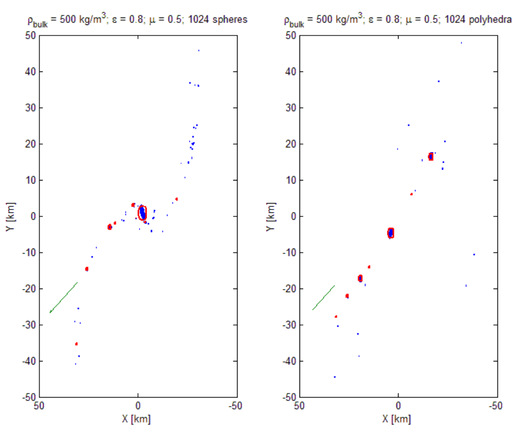


*Figure 1: Comparison of tidal breakup of a comet simulated with different grain geometry, a few hours after perijove.. The left panel shows a simulation using uniform spheres. The right panel is from an identical simulation using randomly generated 12 sided polyhedra. Red circles denote clumps of 3 or more grains.*

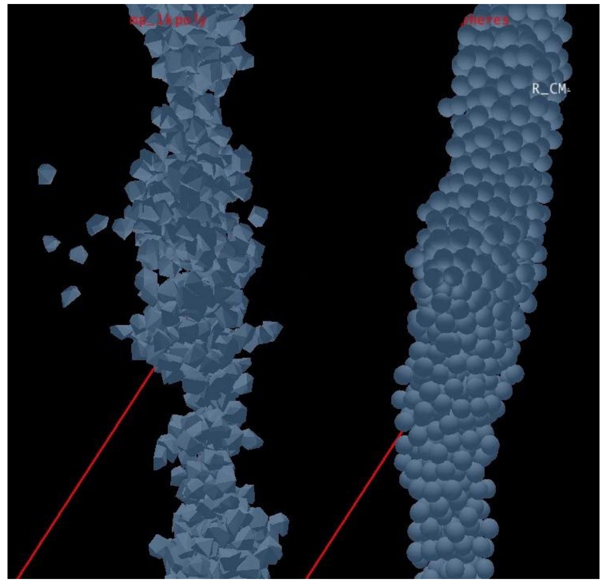


*Figure 2: A frame of the same simulation as Fig. 1, shortly after perijove.*

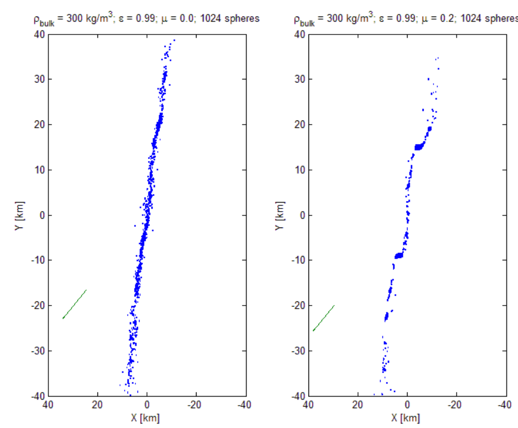


*Figure 3: Comparison of tidal breakup of a comet simulated with (right panel) and without (left panel) intergranular friction.*