EXAMINING THE FORMATION OF SATELLITES IN LARGE CRATERING EVENTS VIA NUMERICAL SIMULATIONS WITH ACCURATE SHAPE MODELS.

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Introduction: The very nature of the size distribution of the asteroids, with greater numbers of small objects than of larger ones, means that for any given asteroid target, small-scale collisions like cratering impacts are far more common than the catastrophic or sub-catastrophic collisions. Cratering impacts too small to cause complete disruption may still produce a quantity of ejected debris that does not immediately re-impact the target asteroid, however. Numerical integrations of the trajectories of impact ejecta around the main-belt asteroid 243 Ida [1] have shown that many debris particles from cratering impacts can temporarily co-exist in complex trajectories about primaries that have irregular shapes. If these particles were to collide/accrete with other ejecta fragments during their flight, it is possible that they could be perturbed enough to enter into bound stable orbits around the primary.

We have tracked the evolution of impact ejecta produced by asteroid cratering/catastrophic disruption events and investigated how such collisions produce satellites as a function of impact initial conditions [2]. Our simulation technique employs two algorithms, one that models the impact phase using a sophisticated smooth-particle hydrodynamics (SPH) code [3], and a second that explores the gravitational evolution of the ejecta over several days of simulation time via a state-of-the-art *N*-body code, `pkdgrav` [4].

For computational expediency, our simulations so far have treated the resulting collision fragments as spheres, such that our models miss the complex gravitational perturbations on impact debris near the largest remnant that are produced by realistic, irregular asteroid shapes.

The observed elongate and irregular shapes of main-belt asteroids 243 Ida and 45 Eugenia, each of which are observed to have small orbiting satellites perhaps formed in large cratering impacts, compels us to examine the effects of this model refinement. Similarly, 87 Sylvia has been found to be accompanied by two small satellites [5], and the large Kuiper Belt object 2003 EL_{61} has been discovered to have associated with it a family of collisional fragments likely produced by a catastrophic collision that stripped much of its icy mantle [6], leaving a rapidly-rotating and elongated remnant with a multiple-satellite system [7].

We have now enhanced our existing simulations of satellite formation in large cratering impacts by conducting SPH simulations of impacts into realistic, irregularly-shaped targets and by computing the *N*-body phase of the simulations using a new version of `pkdgrav` that *preserves the irregular shapes of the reaccumulated largest remnants*. These simulation upgrades are ideally suited to investigating the details of formation scenarios for multiple, small satellites around irregular primaries.

SPH Simulations with Irregularly-shaped Targets: As a proof-of-concept for the new simulation capability, we set up an SPH simulation for an impact into 433 Eros with a shape model that has been reconstructed to remove the scar from the present 5.5-km-diameter Psyche crater. The 82000-particle target was then impacted by a 400-meter diameter projectile at 5 km/s at the approximate present location of Psyche. Our goal here was not to exactly reproduce the circumstances of the Psyche impact, but to complete an end-to-end test of our new simulation capabilities.

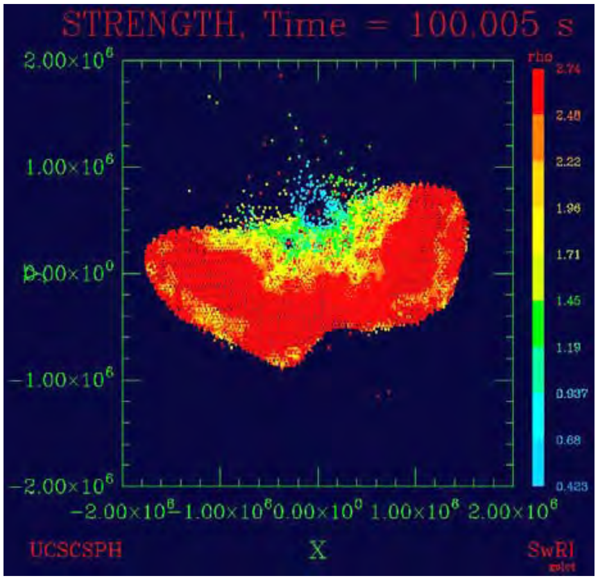

Figure 1. SPH simulation of the impact of a 400-meter diameter projectile at 5 km/s into Eros at the approximate location of the present Psyche crater.

Figure 1 shows the Eros SPH simulation 100 seconds after the impact. For this study, we are primarily interested in the fate of the impact ejecta, but we note the irregular cracks and damage zones propagating away from the impact site. Eros has discrete sets of groove patterns which may have been activated by impact, and it will be interesting to see whether the overall geometry of failure in our impact models starts to have some agreement with observed grooves.

Although all body forces due to the impact are included in the SPH simulation, the code does not allow for initial rotation of the target asteroid. In order to account for the effects of the target's rotation on the ejecta flow field and on the rotation of resulting large fragments, the observed Eros 5.27-hr rotation period is superimposed onto the resulting particle velocities as the positions and velocities of the SPH particles are 'handed off' to `pkdgrav`.

"Rigid" *N*-Body Simulations: The new "rigid" version of `pkdgrav` allows particles colliding with low relative speeds to stick together, creating an aggregate body with shape information, particle history, and complex gravitational field preserved. Aggregate bodies are integrated forward in time using the Euler equations of rigid body motion, with (gravitational) torques applied. The aggregate centers of mass evolve according to the usual laws of motion obeyed by single particles. As particles accrete, they are allowed to 'bounce' into a lower potential energy state before they become part of the aggregate. The degree to which particles bounce before finally sticking is an adjustable parameter within the code. Extremely 'sticky' particles result in very 'fluffy' fractal aggregates [8], while less sticky particles result in more rounded objects with convex profiles. The exact value of the 'stickiness' threshold to use is the subject of continued experimentation. Aggregates can also collide, merge, or break-up due to rotational stresses. The computational cost of the post-aggregate simulation is linear with the number of particles in the simulation.

Figure 2 shows the Eros impact model at two times shortly after the handover to the N-body simulation. Particle colors reflect their reaccretion history, with green representing single, as-yet unaccreted particles. The left panel of Fig. 2 shows the simulation just after the handover from the SPH simulation; the shape of Eros is still recognizable (compare with Fig. 1), most of the particles have not yet aggregated into separate clumps, and the flow of ejecta away from the impact site is evident. The right panel shows the simulation at a later time after substantial particle aggregation has occurred; note the larger irregular fragments and the substantial number of smaller clumped particles – the dynamical history of these particles will be tracked to search for the formation of small bound satellites.

Continuing Work: With a ~100k particle SPH simulation and Eros' volume of about 2525 cubic km, we end up with each particle being the equivalent of a ~180-m diameter chunk of rock. At this stage in our simulation development our *N*-body models include only those particles originally used in the SPH simulation. This leads to a rather coarse treatment of the crater ejecta and smaller debris that we are most interested in tracking in terms of the accretion of small satellites about the primary. A challenge for our ongoing work will be finding ways to include and track smaller particles. One solution is to simply run higher-resolution SPH models, but even doubling the number of SPH particles gets us down to only about ~140-m diameter particles.

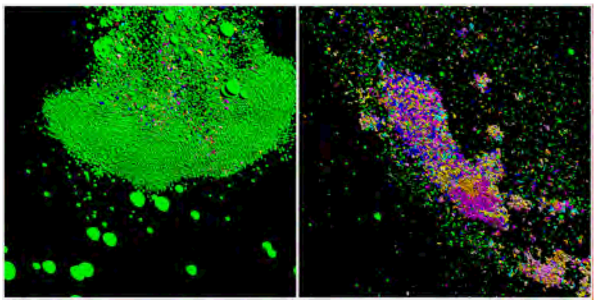

Figure 2. Eros impact model at two different times after handover to the "rigid" version of the *N*-body code `pkdgrav`.

Another possible solution is to replace every SPH ejecta particle with a distribution of ejecta particles – dynamical clones, essentially, but with velocities assigned assuming a linear average between neighboring particle velocities. The clones will not overlap and will add up to the original mass of the particle. In this manner, a single SPH particle will be mapped into a distribution of *N*-body particles following a realistic (e.g. based on the hydrodynamics to that point) velocity dispersion, and thus producing a realistic ejecta flow field.

References: [1] Geissler, P., J.-M. Petit, D. D. Durda, R. Greenberg, W. Bottke, M. Nolan, and J. Moore (1996) *Icarus, 120,* 140–157. [2] Durda, D. D., W. F. Bottke, B. L. Enke, W. F. Merline, E. Asphaug, D. C. Richardson, and Z. M. Leinhardt (2004) *Icarus, 170,* 243–257. [3] Benz, W., and E. Asphaug (1995) *Comput. Phys. Commun., 87,* 253–265. [4] Richardson, D. C., T. Quinn, J. Stadel, and G. Lake (2000) *Icarus, 143,* 45–59. [5] Marchis, F., P. Descamps, D. Hestroffer, and J. Berthier (2005) *Nature, 436,* 822–824. [6] Barcume, K., M. E. Brown, and E. L. Schaller (2006) *Bull. Amer. Astron. Soc., 38,* 565. [7] Brown, M. E., et al. (2006) *Astrophys. J., 639,* L43–L46. [8] Richardson, D. C (1995) *Icarus, 115,* 320–335. [9]