THE FORMATION OF ASTEROID SATELLITES IN CATASTROPHIC IMPACTS: RESULTS FROM NUMERICAL SIMULATIONS. D. D. Durda[1], W. F. Bottke Jr.[1], B. L. Enke[1], E. Asphaug[2], D. C. Richardson[3], and Z. M. Leinhardt[3]. [1]Southwest Research Institute, 1050 Walnut Street, Suite 400, Boulder, CO 80302, [2]University of California, Santa Cruz, Santa Cruz, CA 95064, [3]University of Maryland, College Park, MD 20742.

Introduction: We have performed new simulations of the formation of asteroid satellites by collisions, using a combination of hydrodynamical and gravitational dynamical codes. This initial work shows that both small satellites and ejected, co-orbiting pairs are produced most favorably by moderate-energy collisions at more direct, rather than oblique, impact angles. Simulations so far seem to be able to produce systems qualitatively similar to known binaries (e.g. those tablulated by [1]).

Asteroid satellites provide vital clues that can help us understand the physics of hypervelocity impacts, the dominant geologic process affecting large main belt asteroids. Moreover, models of satellite formation may provide constraints on the internal structures of asteroids beyond those possible from observations of satellite orbital properties alone.

It is probable that most observed main-belt asteroid satellites are by-products of cratering and/or catastrophic disruption events. Several possible formation mechanisms related to collisions have been identified [1]: (i) mutual capture following catastrophic disruption, (ii) rotational fission due to glancing impact and spin-up, and (iii) reaccretion in orbit of ejecta from large, non-catastrophic impacts. Here we present results from a systematic investigation directed toward mapping out the parameter space of the first and third of these three collisional mechanisms.

Numerical Method: Our work takes advantage of a state-of-the-art numerical model that combines results from smooth-particle hydrodynamics (SPH) codes [2], which accurately model the pressures, temperatures, and energies of asteroid-asteroid impacts, and efficient N-body codes [3], which can efficiently track the trajectories of tens-of-thousands of individual collision fragments. This technique of combining the two codes, and preliminary simulation results, have been described in recent publications [4,5]. Simulations using SPH codes are used to model various impacts between colliding asteroids. Once the relevant portions of the impact phase are complete (crater formation/ejecta flow fields established with no further fragmentation/damage), the outcomes of the SPH models are handed off as the initial conditions for N-body simulations, which follow the trajectories of the ejecta fragments for sufficient time to search for the formation of bound satellite systems. Collisions between debris fragments are treated as mergers resulting in a new spherical particle of appropriate combined mass and equivalent diameter. The N-body simulations are run to a time about 4 days after the impact, thus simulating only the initial formation of bound satellites. Long term dynamical evolution of individual satellite systems may be run in future studies.

Model Results: To date we have run 160 SPH/N-body simulations of impacts onto 100-km diameter target asteroids. The non-rotating targets are assumed to be spherical and are composed of solid basalt with a density of 2.7 g cm^{-3}. The spherical basalt projectiles range in diameter from 10 to 46 km, impact speeds range from 2.5 to 7 km s^{-1}, and impact angles range from 15° to 75° (nearly head-on to very oblique).

These results show that energetic (catastrophic) collisions create numerous fragments whose orbits can be changed by (i) particle-particle interactions and by (ii) the reaccretion of material onto the remaining target body. Together, these effects allow some impact debris to enter into orbit around the remaining target body, often a gravitationally reaccreted rubble-pile. We refer to this type of satellite as a SMATS (SMAshed Target Satellite). We also find that numerous smaller fragments escaping the impact site have similar trajectories, such that many become bound to one another. We refer to this type of satellite as an EEB (Escaping Ejecta Binary).

Figure 1 shows the number of SMATS resulting from a collision as a function of the diameter of the largest remnant (a key to symbol colors and sizes is shown in Fig. 4). Since most SMATS debris will eventually either reaccrete onto the primary or accrete with other SMATS debris while in orbit, the number of SMATS particles may be crudely related to the eventual size of the single satellite that will likely remain in orbit about the largest remnant. In this and the following figures, sub-catastrophic (low energy) impacts are represented to the far right and supercatastrophic (high energy) to the far left. It appears that most SMATS are formed around the largest remnants of moderately catastrophic impacts, in which the mass of the largest remnant is less than half that of the original target. For our 100-km diameter targets this translates to those largest remnant diameters of 80 km or less. At lower impact energies the events are essentially large cratering impacts and most ejected material eventually reaccretes onto our spherical remnants, leaving little orbiting material. At very high impact energies targets are severely disrupted, resulting in small largest remnant sizes and less bound debris. We find that most

SMATS are formed from low-angle rather than oblique impacts.

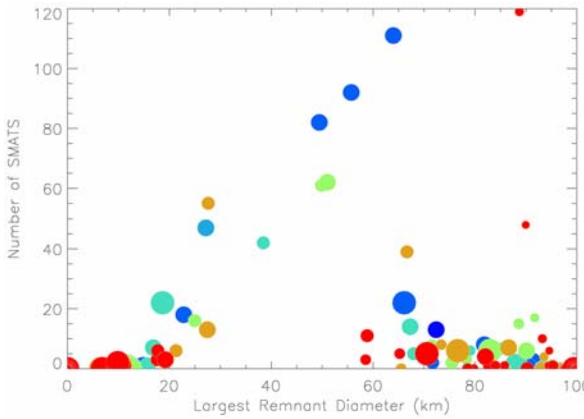

Figure 1. Number of SMATS versus the diameter of the largest remnant.

Figure 2 shows the number of EEBs as a function of the diameter of the largest remnant. As for the number of SMATS, it appears that most EEBs result from moderately catastrophic impacts, although many are also produced by the highly disruptive impacts resulting from large projectiles striking at or below the average main-belt mutual impact speed of ~5 km s^{-1}. Other large impactors striking at higher speeds evidently eject collision debris so energetically that few escaping fragments can remain bound to each other.

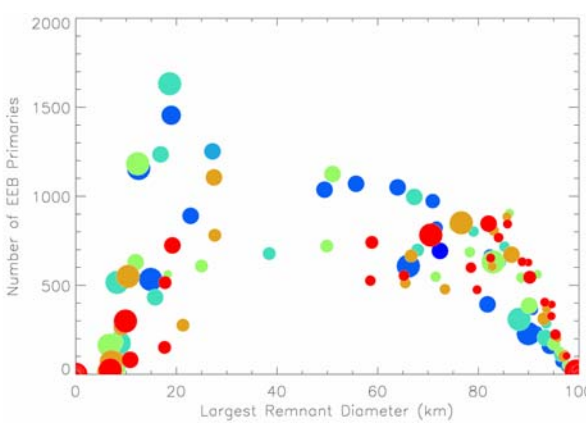

Figure 2. Number of EEB primaries versus the diameter of the largest remnant.

Figure 3 shows the diameter of the largest EEB primary resulting from each impact as a function of the diameter of the largest remnant. Very energetic and highly disruptive impacts produce smaller EEB systems.

The 3 large blue dots near the peak in the number of SMATS in Fig. 1 are also the same 3 near the peak in the number and size of EEBs in Figs. 2 and 3. These points represent impacts of 34-km diameter projectiles at 3 km s^{-1} at impact angles of 25°–35°. Such impacts appear very efficient at producing relatively large satellites around the largest remnant as well as large numbers of modest-size binaries among their escaping ejecta.

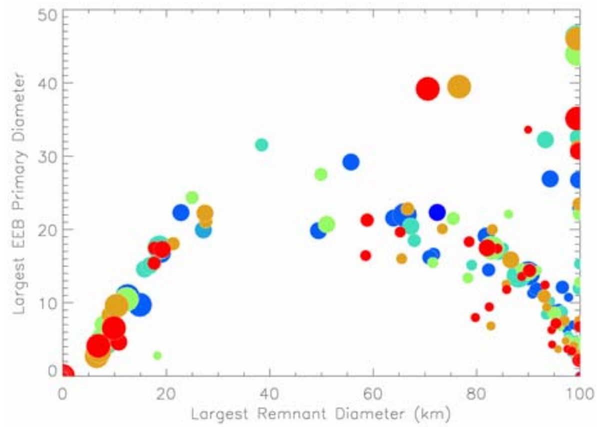

Figure 3. Diameter of the largest EEB primary versus the diameter of the largest remnant.

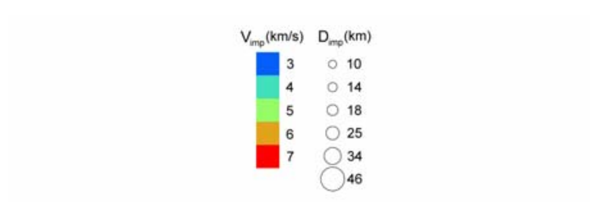

Figure 4. Key to symbol colors and sizes for Figs. 1–3. Dot colors are coded according to impactor speed and dot sizes are coded according to impactor diameter.

As of this writing we have only considered non-rotating homogeneous spherical targets; our future work shall explore the importance of shape, internal structure and rotation on asteroid breakup and satellite formation.

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