BINARY ASTEROIDS: PROGENITORS OF DOUBLET CRATERS W. F. Bottke, Jr. and H. J. Melosh, Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721.

Three of the 28 known impact craters on Earth with diameter $D > 20$ km are doublets (i.e. have a companion crater nearby) created by the nearly simultaneous impact of objects of comparable size [1]. A significant number of craters on the other terrestrial planets are also doublets, though only Venus has been surveyed quantitatively [2]. Recent radar observations of Earth-crossing asteroids (and possibly Galileo observations of Gaspra and Ida) show shapes that suggest that some of these bodies are composed of two or more agglomerated components (e.g. 4769 Castalia and 4179 Toutatis) [3]. Such bodies could produce doublet craters if their components separate before impact.

What mechanism is capable of separating the components of a binary asteroid before planetary impact? Tidal disruption during the binary asteroid's final approach and break-up due to atmospheric friction, discussed in [1], is insufficient to produce significant separation of the components. However, Farinella [4] proposed that some asteroids, after experiencing a close approach with a planet, break into two (or more) fragments which begin to orbit one another. In many cases, these orbiting pairs re-encounter and impact the planet during a later pass, creating two distinct craters. Analytic work by both Farinella [4] and Chauvineau *et al.* [5] suggests that binary asteroids encountering the Earth can have their orbital energy significantly modified by tidal perturbations, causing the components to (a) collide, (b) escape from one another, or (c) go into mutual orbit. Endstate (c) is directly applicable to doublet crater production, since the components are most likely to be near their furthest extension (*i.e.* aphelion) at impact.

To quantify this process, we developed a model which numerically integrates close encounters between individual binary asteroids and the Earth (i.e. encounters inside Earth's Hill sphere). For each run, we started thousands of contact-binary asteroids initially far from the Earth (e.g. at 20 Earth radii) with a random initial orientation, a selected encounter velocity V_∞, and a selected planetary close approach distance d. We then tabulated the endstate results for each set of initial conditions and the separation distances for binary asteroids left orbiting each other after Earth encounter (Fig. 1). We found that loosely-bound contact binaries encountering the Earth at distances less < 5 Earth radii can become well separated, confirming the general results of Chauvineau *et al.* [5]. In addition, we found that the distance between these components can increase with additional planetary encounters.

Next, to verify that the binary asteroids/tidal forces can produce doublet craters, we combined the "binary asteroid encounter model" described above (i.e motion inside a planet's Hill sphere) with a Monte-Carlo dynamical evolution model used by Bottke *et al.* [6] to simulate the orbital evolution of asteroids in the terrestrial planet region (i.e. motion outside a planet's Hill sphere). Monte-Carlo codes [7, 8] compute the probability that a given binary asteroid will encounter one of the terrestrial planets, but they do not actually integrate the orbit of each body. These models also assume that both the planets and test bodies are on unperturbed keplerian orbits (with uniformly precessing apsides and nodes) around the Sun. As such, test bodies are considered unperturbed unless they enter the a planet's sphere of influence (Hill sphere), where they either (a) collide with the planet, or (b) experience a ΔV during a two-body encounter. This process is repeated until the test body impacts a planet, is disrupted by an asteroid collision, or is ejected from the system through a close approach with a Jovian planet. To determine the final separation distance between the components at impact, we also include an "impact encounter model" which accounts for tidal perturbations on the binary asteroid during its final approach and the trajectory of the components near the planet.

For the run shown in Fig. 2, we start 5000 contact binary asteroids in the region of space where the 3:1 and ν_6 resonances cross the orbit of the Earth (e.g. orbital parameters a = 2.5 AU, e = 0.6; 0.65; 0.7, i = 5° for the 3:1 resonance, a = 2.1 AU, e = 0.524, i = 5° for the ν_6 resonance). If the components escape one another during a planetary encounter, both components are removed from the run. Separation distances between the components are recorded upon planetary impact.

We find that our results are consistent with Earth's cratering record; ~5% of the binary asteroids impacting the Earth are separated by 10 times (or more) of their mean diameters. We also find that the other terrestrial planets (e.g. Venus, Mars, the Moon) should have doublet craters as well. These results imply that many large near-Earth asteroids evolve into and thus currently are binary asteroids. They also yield two implications for those interested in protecting the Earth from impacting comets or asteroids: Large bodies near the Earth may be more fragile than expected, and that deflection of these bodies on an impact trajectory with Earth may be difficult, since there could be more than one target. Future work will address mutual tidal effects and the effects from multiple (2+) fragments.

References: [1] Melosh H. J., and Stansberry, J. S. (1991) *Icarus*, **94**, 171. [2] Cook C. *et al.* (1995) *Venus II* conference. [3] Ostro S. J. *et al.* (1990), *Science* **248**, 1523.; (1993), *BAAS*, **25**, 1126. [4] Farinella, P. (1992), *Icarus*, **96**, 284. [5] Chauvineau *et al.* (1994), *Icarus*, to be submitted. [6] Bottke, W. F. (1994), *ASP Proceedings*, in press. [7] Arnold, J. R. (1965) *Astrophys. J.* **141**, 1536. [8] Wetherill, G. W. (1985) *Meteoritics* **20**, 1.

Fig. 1:

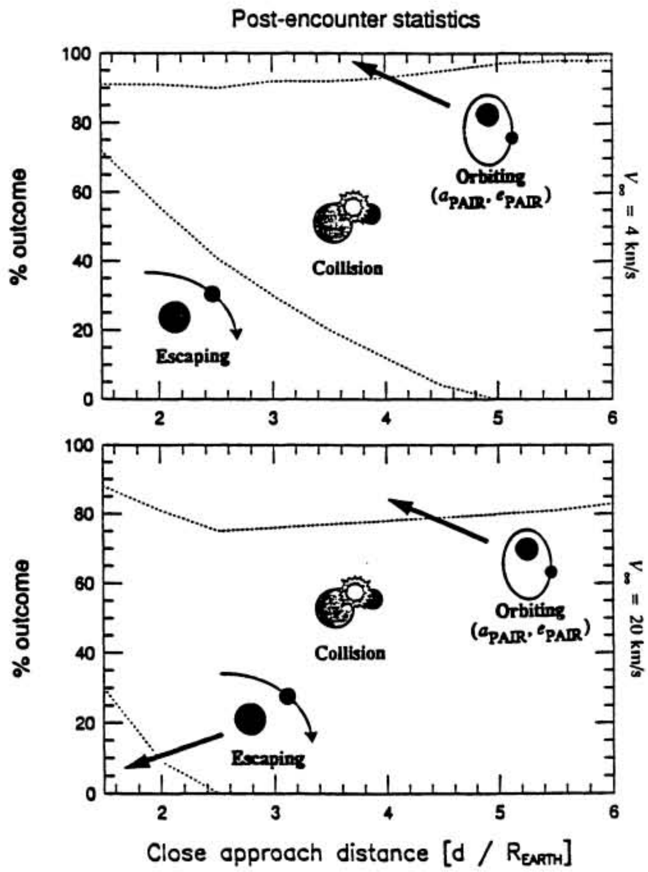

Fig. 2:

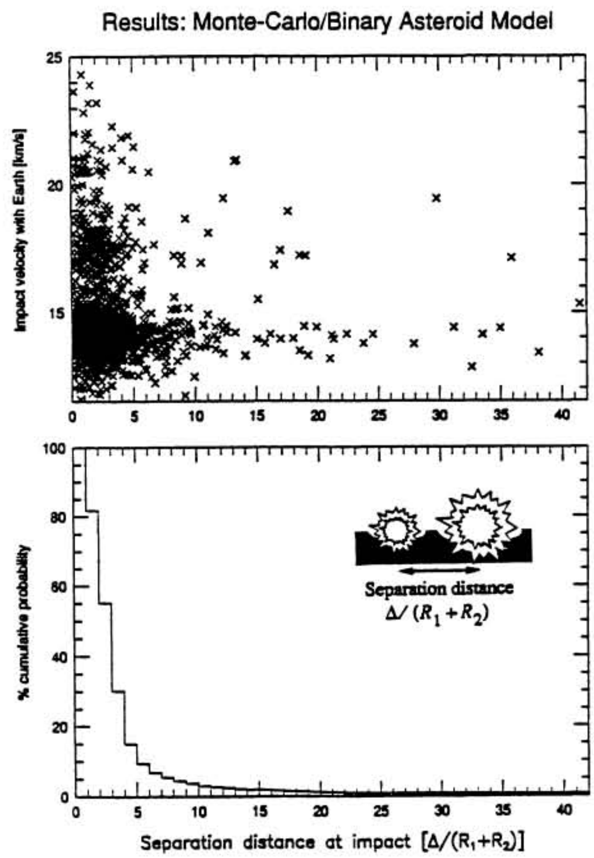

Fig. 1: Post-encounter statistics for contact binaries encountering the Earth at two initial velocities (V_∞ = 4 km/s; 20 km/s) and various close approach distances (d between 1.5 and 6.0 Earth radii). Over 10,000 runs were made for each choice of V_∞ and d, all at random initial orientations. Starting distance was 20 Earth radii.

Fig. 2: Results from our Monte-Carlo/Binary Asteroid model showing the separation distance between binary asteroid components impacting the Earth vs. (a) impact velocity and (b) cumulative number of binary asteroids impacting the Earth. Note that nearly 5% of these binaries impact at separation distances > 10 (or more) times their mean diameters.