DOUBLET CRATERS ON MARS W. F. Bottke, Jr. (Division of Geological & Planetary Sciences, California Institute of Technology, Mail Code 170-25, Pasadena, CA 91125) and H. J. Melosh (Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721).

A recent survey of Mars' northern plains by Ingrham et al. [1] found a surprising paucity of doublet craters (a few percent) compared with the fraction of doublets found on Earth (with diameters larger than 20 km) [2] and Venus (~10%) [3]. Doublet craters are formed from two well-separated asteroids impacting a planetary surface at nearly the same time, such that two distinct craters are formed. Previous results [2, 4, 5] have shown that these asteroids must be separated well in advance of planetary impact, implying that a small but substantial number of asteroids must have satellites. Using a numerical model, we have found that loosely bound asteroids ("rubble piles") encountering Earth or Venus may be pulled apart into large fragments by planetary tidal forces, which under certain circumstances may remain gravitationally bound to one another [4, 5]. We have also found that many of these co-orbiting binary asteroids impact the Earth or Venus while well-separated, and that we can reproduce the fraction of doublet craters found on Earth and Venus [5]. We have now modified our numerical model to investigate asteroids encountering Mars. We find that although Mars' lower density does not prevent loosely bound asteroids from being pulled apart into large fragments, only a small fraction of these binaries become well-separated. Accordingly, our model predicts that less than 3% of the asteroids impacting Mars produce doublet craters, matching observations [1].

Well-separated co-orbiting asteroids are necessary to produce doublet craters, since km-sized asteroids cannot break into two well-separated components through atmospheric friction effects nor from the pull of planetary tidal forces just before impact [2]. Moreover, we have shown (using a Runga-Kutta numerical integrator [6]) that asteroid experiencing a close encounter with the Earth may be pulled into multiple co-orbiting fragments by the planet's gravitational tidal forces [4]. Incorporating this model into a Monte-Carlo model that computes the frequency and characteristics of repeated multiple encounters with the Earth (or Venus), we have shown that Earth and Venus can produce a steady-state population of well-separated binary asteroids if those bodies were initially loosely bound ("rubble piles") and were fast rotators [5].

We now apply this Monte-Carlo binary asteroid model to Mars to determine whether Mars can produce a noticeable signature of doublet craters on its surface. We start with a population of spherical contact-binaries (0.5 and 1.0 km in radius with a rotation period of 3.55 hours and a density of 2600 kg/m^3) to evolve over multiple passes with Mars using a probability distribution of relative encounter velocities "at infinity" (from 2 - 38 km/s, incremented by 4 km/s) [7]. 90 bodies were run in the Monte-Carlo code for each velocity increment, and each asteroid can evolve for as long as 100 Myr, though this value is almost certainly an upper limit; recent results [8] show that asteroids entering newly found resonances in the solely Mars-crossing asteroid region can become Earth-crossing much sooner than previously expected by Monte-Carlo models. If a close Mars encounter produces a co-orbiting asteroid, distant Mars encounter and mutual tides between the components may cause them to become well separated (if their the components do not escape from each other or collide with one another first). We find that well-separated binary asteroids are extremely likely to become unbound during planetary close approaches. However, the same planetary approaches that cause binary components to escape often produce new binary components from the remaining mass of the "rubble-pile", allowing the binary population to reach steady-state over time.

Our results show that while Mars' tidal forces can readily pull the loosely bound bodies apart after a few Myrs, they typically do not create well-separated components even after 100 Myr of dynamical evolution (Fig. 1). We find that only 16% of the fast rotating rubble-piles asteroids that encounter Mars become separated by distances larger than 10 times them mean diameter, the typical distance needed to produce a doublet crater. If we scale this result by the fraction of the asteroid population that

DOUBLET CRATERS ON MARS: Bottke, W. F. and Melosh, H. J.

actually have fast rotation rates (i.e. have less than 5.5 hour rotation periods) (28%) [9], we find that only 5% of asteroids encountering Mars become well-separated binary asteroids. In comparison, 15% of the asteroids that encounter Earth become well-separated.

To determine the fraction of this population that form doublet craters on Mars, we modeled impact encounters between binary asteroids and Mars using a Runga-Kutta numerical integrator [6], which accounted for the asteroid's encounter and impact velocities and the trajectory and orientation of the components at impact. Our results show that only 3% of all of the asteroids that impact Mars form doublet craters (Fig. 2), matching Ingrham et al.'s survey results [1].

These results provide important verification for our scenario describing the origin of doublet craters, since our model can match the fraction of doublet crater found on Venus, Earth, and Mars (the other terrestrial planets have not been surveyed). Moreover, the different doublet crater fractions seen between Earth/Venus and Mars make it unlikely that doublet craters could come from a population of well-separated binary asteroids formed in the main-belt (e.g. Ida and Dactyl), since such a population would produce the same fraction of doublet craters on all the terrestrial planet (presuming, of course, that a means could be found to keep the binaries bound through numerous planetary close encounters).

References: [1] Ingrham, J. et al. (1996) *LPSC XXVII.* [2] Melosh H. J., and Stansberry, J. S. (1991) *Icarus*, **94**, 171. [3] Cook C. *et al.* (1995) *LPSC XXVI;* also submitted to *Icarus.* [4] Bottke, W. F. and Melosh, H. J. (1995) *LPSC XXVI.* [5] Bottke, W. F., and Melosh, H. J. submitted to *Nature.* [6] Press et al. (1986) *Numerical Recipes.* [7] Bottke et al. (1995) *Hazards Due to Comets and Asteroids.* 326. [8] Gladman et al. (1996) submitted to *Science*. [9] Harris, A. personal communication.

Fig. 1:

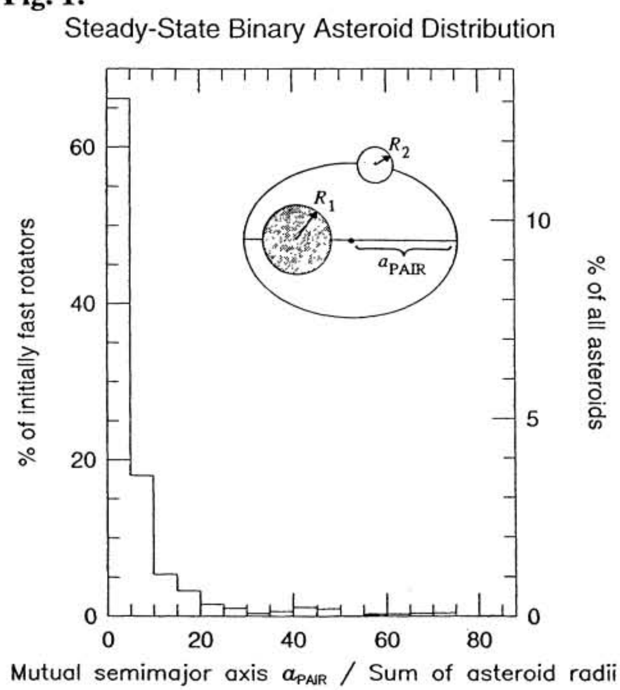

Fig. 2:

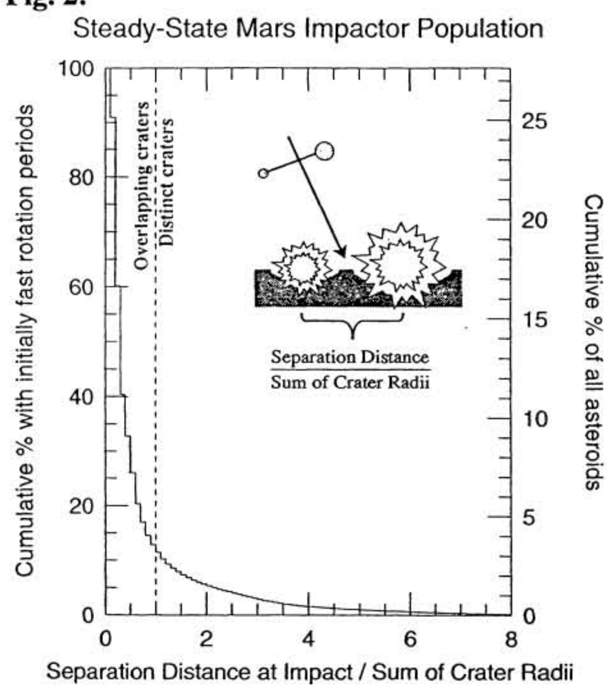

Fig. 1: The steady-state distribution of co-orbiting asteroids that encounter Mars (only). The abscissa shows their mutual semimajor axis (in units of the sum of the component's radii). The (left/right) ordinate shows the percentage of (initially fast rotating objects/all asteroids) which evolve into binary asteroids.

Fig. 2: The fraction of objects impacting Mars that produce doublet craters. The abscissa shows the separation distance between the components over the sum of the crater radii. The (left/right) ordinate shows the cumulative number of (initially fast rotating objects/all asteroids) which impact Mars at a given separation distance or smaller.