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Binary Asteroids and the Formation of Doublet Craters

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At least 10% (3 out of 28) of the largest known impact craters on Earth and a similar fraction of all impact structures on Venus are doublets (i.e., have a companion crater nearby), formed by the nearly simultaneous impact of objects of comparable size. Mars also has doublet craters, though the fraction found there is smaller (2%). These craters are too large and too far separated to have been formed by the tidal disruption of an asteroid prior to impact, or from asteroid fragments dispersed by aerodynamic forces during entry. We propose that some fast rotating rubble-pile asteroids (e.g., 4769 Castalia), after experiencing a close approach with a planet, undergo tidal breakup and split into multiple co-orbiting fragments. In some cases these fragments evolve into stable binary systems, which re-encounter and impact the planet during a later pass, creating two distinct craters.

To test this idea, we modeled close encounters between fast-rotating contact-binary asteroids, our first-order approximation for rubble-pile asteroids, and a chosen planet. Our results show that Earth's tidal forces frequently create binary asteroids, but that the separation distance between the binary's components is almost always too small to produce a doublet crater at impact. However, once the components are orbiting one another, small perturbations from repeated distant Earth enounters, along with mutual tidal forces between the components, frequently increase the separation distance between the components in a random-walk fashion. To model these effects, we combined our numerical model of planetary encounters with a Monte Carlo code that computes the frequency and characteristics of repeated Earth encounters as well as mutual tidal effects occurring between Earth encounters. Our results show that ~15% of all Earth-crossing asteroids evolve into co-orbiting binary asteroids with well-separated components. Asteroids on solely Mars-crossing orbits produce a smaller fraction of binaries (<5%).

Folding these results into another model treating impact encounters between binary asteroids and a chosen planet, we found we could duplicate the observed fraction of doublet craters found on Earth, Venus, and Mars. Our results suggest that any search for asteroid satellites should place emphasis on km-sized Earth-crossing asteroids with short-rotation periods.

1. INTRODUCTION

Two commonly held paradigms about asteroids and comets are that (a) they are composed of non-fragmented chunks of rock or rock/ice mixtures, and (b) they are solitary bodies. However, several discoveries made in 1993–1994 are inconsistent with those interpretations, and they are helping to revolutionize our understanding of what asteroids and comets are like.

One such discovery was that of disrupted comet P/Shoemaker–Levy-9's (SL9), whose pieces later went on to impact Jupiter, Few expected comets to be so weak that Jupiter's tidal forces could pull one of them into over 20 similar-sized fragments. In hindsight, the observation of crater chains on Ganymede and Callisto, which are now recognized as the impact remnants of previous SL9-type events at Jupiter (Melosh and Schenk 1993), suggest that many comets (and asteroids) may, in fact, be rubble piles, a collection of gravitationally self-bound components ranging in size from micrometers up to 100 m or km-sized fragments. Rubble piles are more susceptible to the effects of small differential gravitational forces than consolidated bodies, and thus are more likely to produce SL9-type fragmentation events (Asphaug and Benz 1996). The discovery of crater chains on the Moon similar to those found on the Galilean satellites shows us that rubble piles approach the Earth as well, and that the Earth's tidal forces can also

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pull apart small bodies (Melosh and Whitaker 1994). That, along with other evidence we present in Section III, suggests that our understanding of the internal structure of small bodies may need revision.

Another discovery was the Galileo spacecraft's detection of a small km-sized asteroid (now named Dactyl) orbiting 243 Ida (Belton *et al.* 1994, Chapman *et al.* 1995). Though asteroid satellites have been discussed for years and circumstantial evidence suggested they existed (extremely slow asteroid rotation rates, anomalous asteroid lightcurves and occultation ''blink-outs,'' radar images of bifurcated near-Earth asteroids, doublet craters, etc.—see Section VII for more information), most scientists were still surprised to find a satellite orbiting only the second main-belt asteroid ever imaged. The repercussions of Galileo's discovery shifted the conventional wisdom within the asteroid community from skepticism about the existence of asteroid satellites to a more enlightened view that asteroid satellites may help to explain unusual asteroid and crater phenomena.

By reinterpreting the nature of asteroids and comets, we may now be able to explain the mysterious impact phenomenon known as doublet craters. These impact structures, which so far have been found on the Earth, Moon, Venus, and Mars, are created by the nearly simultaneous impact of objects of comparable size. No satisfactory explanation for their origin has yet been proposed, though several attempts have been made over the years. In this paper, we propose a mechanism for their formation, which if true, leads to the possibility that many near-Earth asteroids have satellites produced by the Earth's tidal forces. However, before we discuss our model and its results, we first describe the record of doublet craters on the terrestrial planets.

II. THE DOUBLET CRATER IMPACT RECORD ON THE TERRESTRIAL PLANETS

II.A. Earth

Doublet craters make up a substantial fraction of Earth's crater population. At least 3 of the 28 largest impact structures with diameters greater than 20 km have a companion crater nearby sharing the same formation age (Table I). (Melosh and Stansberry 1991). Of these three, only East and West Clearwater Lake craters are roughly the same size; the other two doublets have large components (Ries and Kamensk) nearly an order of magnitude larger than their smaller components (Steinheim and Gusek, respectively), implying their progenitors must have had a similar size ratio.

Since that paper, additional doublet craters have been suggested in various regions around the world, though all of these claims are controversial; Earth's high erosion rates make it difficult to both find craters (especially small craters) and to determine their formation age. Not all craters within close proximity to one another are doublets. For example, the Wanapitei Lake crater in Ontario, Canada sits inside the Sudbury basin, yet its age of formation is nearly 1 Gyr younger than the Sudbury basin (37 Myr vs 1800 Myr) (Grieve and Shoemaker 1994). Nevertheless, we report the claims that have come to our attention: Ernstson *et al.* (1994) and Ernstson and Fiebag (1993) suggest that the Azuara impact structure (35–40 km) and the nearby Rubielos structure (of comparable size) in Spain may, in fact, be a doublet. However, neither site has been dated and even their interpretation as impact structures is contested by Aurell *et al.* (1993) and by Langenhorst and Deutsch (1996). Though intriguing, more work is clearly necessary. Another controversial doublet crater is Kara/Ust-Kara in Siberia, of which the Kara crater is located on land and the Ust-Kara crater is located mainly underwater. Recent reconstructions of the Kara impact structure based on gravity data, altimeter measurements, and geological and goechemical considerations suggest that Kara/Ust-Kara may be part of a single impact structure (Nazarov *et al.* 1992), though these results are not considered conclusive (B. Ivanov, personal communication). Finally, a small companion crater (400 m) has recently been found 3 km southwest of the Pretoria Saltpan crater (1.13 km) in South Africa (Brandt *et al.* 1994). Gravity anomaly tests performed on both South African craters suggest that they were formed by impacts, though these tests do not tell whether these craters are associated with one another. Given the nature of the data, we feel it is premature to include any of these structures into our doublet crater database at this time.

II.B. Venus

Since few doublet craters are found on Earth, and the overall impact crater record on Earth is sparse, eroded, buried by sediments, and biased against small impactors, it is important to characterize the doublet crater population on Venus, especially since, to first order, the asteroid population impacting its surface is the same as that impacting Earth. Surveying Venus for doublet craters has a number of advantages over Earth: (a) the surface of Venus was resurfaced 300–500 Myr ago, eliminating most/all craters (Strom *et al.* 1994) (b) Venus has extremely low erosion rates, and (c) Venus' crater population (935) (Schaber *et al.* 1995) is larger than Earth's (140) (Grieve and Shoemaker 1994), potentially allowing better crater statistics, but is not so large as to produce an overwhelming number of chance associations.

Cook *et al.* (1995; 1996) recently completed a quantitative survey for doublet craters on Venus. Their comparison between observations and the predictions from a randomly distributed crater model suggested that the double crater

TABLE I
Terrestrial Doublet Craters

Crater pair	Crater age (Myr)	Crater diameter, D (km)	Projectile diameter, L (km)	Separation, Δ (km)	Separation, Δ/(Sum of proj. radii)
W. Clearwater Lake	290 ± 20	32	3.3	28.5	11
E. Clearwater Lake	290 ± 20	22	2.1		
Ries	14.8 ± 0.7	24	2.3	46	37
Steinheim	14.8 ± 0.7	3.4	0.20		
Kamensk	65	25	2.4	15	7.5
Gusev	65	3	0.16		

Source. Melosh and Stansberry 1991.

abundance on Venus was only ~2.2%, much lower than Earth's abundance (~10%). However, they believe that the apparent paucity of doublet craters was produced by Venus' dense atmosphere, which screens out smaller members of true doublets. Craters smaller than 2 km are not found on Venus (Herrick and Phillips 1994), implying that bodies <200 m or so in diameter do not survive passage through Venus' atmosphere. Applying the same screening effect to Earth they found that two of its three doublet craters would be eliminated (Steinheim and Gusev are both small companion craters formed by the impact of a ~200 m asteroid). By removing these doublets from the doublet data base (Table I), Cook *et al.* found that the Earth's proportion of doublet craters nearly matches Venus (1 out of 28, or 3.6%).

However, Cook *et al.* found better evidence that the fraction of binaries impacting Venus matches the fraction impacting Earth. Asteroids hundreds of meters in size frequently undergo a Tunguska-like catastrophic disruption in Venus' atmosphere, leaving behind a characteristic radar-dark pattern on Venus' surface called a ''dark splotch'' (Schaber *et al.* 1992, Zahnle 1992). Cook *et al.* investigated these ''dark splotches'' for doublets, only counting those that were separated by a large enough distance that spreading by aerodynamic forces could be ruled out as a mechanism. To rule out chance associations, they compared their splotch separation results with a random-distribution of splotches on Venus' surface. They found that 57 out of the 400 Venus splotches (~14%) were doublets, far in excess of the 2–3% predicted by a random distribution of impacts. Thus, with all these factors taken into account, Cook *et al.* (1996) determined that the fraction of doublet impact structures on Venus was not statistically different from the fraction of doublet craters on Earth (~10%).

II.C. *Mars, Mercury, and the Moon*

The remaining terrestrial planets are more difficult to survey quantitatively for doublet craters. Much of the surfaces of Mars, Mercury, and the Moon are nearly saturated with craters, implying that older, smaller craters have been erased by asteroid bombardment. Moreover, when many craters are close to one another, it becomes nearly impossible to discern true doublets based on crater morphology. Instead, one must resort to crater distance statistics, which are dependent on variables such as the size-frequency distribution of the impacting asteroid population and rate of crater-erosion/obliteration at different sizes, both which are coupled and may vary with time.

An example of the pitfalls of using crater statistics to determine doublets was demonstrated by Oberbeck and Aoyagi (1972), who presented a statistical survey of doublet craters on Mars. By examining photographs from Mariner 6 and 7, and by creating a Monte Carlo model to simulate Martian crater formation, they attempted to show that an abnormally large number of Martian doublet craters existed compared to the number expected from a model producing a random distribution of craters. From their results, they inferred that some process, probably planetary tidal forces, was causing asteroids to break apart and separate before impact. They also performed similar statistical searches on Mercury and the Moon, which also yielded a higher ratio of doublet craters than expected from a random distribution (Oberbeck *et al.* 1977).

These claims were disputed by Woronow (1978a), who reanalyzed Oberbeck and Aoyagi's model and made their own Monte Carlo model to simulate Martian crater formation. Woronow's model included factors that Oberbeck and Aoyagi's model had neglected, such as crater obliteration, varying crater sizes, and varying production populations of impactors. Woronow found that the number of doublets depends strongly on the slope of the production population's size–frequency distribution and the distance discriminant used to classify doublet/non-doublets. Testing a range of parameters, Woronow (1978a) was able to match the observed number of doublets with his model results. Thus, he concluded that Oberbeck and Aoyagi's model had underestimated the number of chance associations; the actual number of true doublets on Mars found in heavily cratered regions were probably only a few percent of all crater pairs. Oberbeck (1978) attempted to refute Woronow's claims, but Woronow (1978b) defended his critique by introducing Oberbeck's objections (mostly based on Woronow's choice of distance discriminate for doublets) into his model and showing they made no difference.

A more quantitative survey of doublet craters on Mars was reported by Melosh *et al.* (1996), who investigated the lightly cratered northern plains of Vastitas Borealis. They investigated all possible craters pairs (with diameters >5 km) over ~2 million square kilometers of terrain using the same criteria used by Cook *et al.* (1995, 1996) (see Section II.B). They found 3 craters (out of 133) that were good candidates for true doublets (2 ± 1%). The remaining crater pairs were not distinguishable from those found by a random crater population, implying that the fraction of doublet craters on Mars could only be a few percent at best.

In conclusion, the doublet craters records found on Earth, Venus, and Mars provide an important constraint on any model that would describe doublet crater formation: Such a model must not only account for the large doublet population found on Earth and Venus (~10%) but also the small doublet population found on Mars (~2%).

III. PREVIOUS WORK

What type of progenitors could produce doublet craters at impact? One possibility is that an Earth-crossing contact-binary asteroid such as 4769 Castalia (Ostro *et al.* 1990, Hudson and Ostro 1994) or an Earth-crossing asteroid composed of fragments which are gravitationally bound to one another (a "rubble-pile" asteroid) could produce a doublet crater if the objects could be pulled into well-separated components before impact. To this end, there is a substantial amount of evidence that many km-sized near-Earth asteroids are rubble piles: (a) Observations of small main-belt asteroids 951 Gaspra (Belton *et al.* 1992), and 243 Ida (Belton *et al.* 1994) by the Galileo spacecraft show an elongated appearance, extremely large craters relative to the size of the bodies, and large amounts of regolith, all implying that many small asteroids are fragmented bodies possibly containing several large coherent chunks of debris (Greenberg *et al.* 1994, 1996); (b) Radar studies of near-Earth asteroids (e.g., 4179 Toutatis (Ostro *et al.* 1995a); 1620 Geographos (Ostro *et al.* 1995b)) and photometric lightcurve measurements of near-Earth asteroids (McFadden *et al.* 1989) indicate a substantial fraction have elongated and/or irregular shapes; (c) No asteroid has yet been found which rotates faster than its theoretical breakup limit, implying that many/most asteroids have little or no tensile strength and are rubble-piles (Harris 1996); (d) Numerical results from hydrocode models simulating asteroid collisions suggest that even an initially undamaged asteroid can become highly fractured after a few (or a single) impact(s), though large internal blocks can remain intact (Asphaug and Melosh 1993, Greenberg *et al.* 1994, 1996, Nolan *et al.* 1996, Love and Ahrens 1996).

Since rubble-pile asteroids would have little internal strength, there is no need to fragment the asteroid or rip apart coherent rock to separate their components before impact. However, even when using such loosely bound asteroids, several potential mechanisms for forming doublet craters do not work:

(1) Tidal disruption of a contact-binary asteroid during its impact approach to a planet: This mechanism was most recently (and most thoroughly) investigated by Melosh and Stansberry (1991), who created a numerical model simulating planetary tidal stresses on fast rotating contact-binary asteroids approaching and impacting the Earth. After testing thousands of encounters, they found that planetary tidal forces were incapable of significantly separating the components tangentially as they approached the Earth, except for a few rare cases where the binaries impacted at low angles relative to the surface (<1%). However, even if the low-angle impacts were more common, they would still be an unlikely mechanism for forming doublet craters, since few doublets on Earth, Venus, and Mars show evidence that they were formed by oblique impacts (e.g., asymmetric ejecta blankets and/or elliptical shapes).

(2) Atmospheric friction causing the breakup of a mechnically weak asteroid on an impact encounter: Passey and Melosh (1980) were among the first to quantitatively model the catastrophic break-up of meteoroids in Earth's atmosphere. In test runs, they saw that small bolides entering the atmosphere are crushed by aerodynamic stresses, increasing each bolide's cross section until they catastrophically disrupt, frequently creating multiple fragments (Chyba *et al.* 1993). However, the disruption itself does not significantly separate the fragments. Bow-shock interactions between the fragments often yield tangential velocities as large as a few hundred meters per second, causing them to spread and impact in different locations (Passey and Melosh 1980). However, the maximum separation achievable by this mechanism is not much larger than 1 km on Earth or 10 km on Venus, except, again, for the rare very low angle approach trajectories (Cook *et al.* 1996).

A different approach to forming doublet craters was suggested by Farinella (1992). He hypothesized that Earth-crossing binary asteroids with small mutual orbits, formed by catastrophic collisions in the main asteroid belt (Durda 1996), could be pulled into well-separated binary asteroids (or into contact-binary asteroids) by planetary tidal forces.

The orbiting endstate would be directly applicable to the formation of doublet craters, since the well-separated co-orbiting components could re-encounter and impact a planet during a later pass, forming two distinct craters. His approximate analytical approach showed that binary asteroids have their orbital energy changed enough by close planetary encounters that the separation distance between the components increases significantly.

Farinella's (1992) analytical approach was followed up by Farinella and Chauvineau (1993), who derived a more sophisticated analytical method to follow the evolution of binary asteroids encountering Earth, and Chauvineau *et al.* (1995), who developed a Monte Carlo scheme to follow the evolution of binary asteroids encountering Earth over multiple passes until they escaped with one another or collided. Thus, a contact binary would be an endstate for their model. In both papers, binary asteroids encountering Earth have their component's mutual orbital energy (E) and angular momentum (L) modified by small variations (ΔE and ΔL) depending on parameters such as the binary's encounter orientation, its impact parameter, and its encounter velocity. The timescale between successive encounters was determined by that body's encounter probability with Earth, scaled by a random deviate. Chauvineau *et al.* (1995) also included the mutual tidal effects of both components on each other after Earth encounter. These mutual tidal effects modify the final mutual semimajor axis (a_{PAIR}), eccentricity (e_{PAIR}), and spin states of the components. Chauvineau *et al.* found that binaries initially separated by a small distance often become well separated through successive Earth encounters, though a large fraction (from 25 to 50%) ended up contact-binaries and a comparable fraction end up escaping from one another after 20 Myr of evolution. Thus, since their results imply that few (if any) binary asteroids formed in the main-belt survive to impact the Earth or Venus (escapes or collisions were far more common), their model could not explain the large fraction of doublet craters found on either body. Furthermore, their model could not account for the small fraction of doublet craters on Mars.

IV. THE FORMATION OF ASTEROID SATELLITES BY PLANETARY TIDAL FORCES

IV.A. Hypothesis

We propose a different mechanism to produce doublet craters, one which takes advantage of some of the ideas proposed by Farinella (1992), Farinella and Chauvineau (1993), and Chauvineau *et al.* (1995) yet is independent of their work. We propose that contact-binary asteroids or rubble-pile asteroids, after experiencing a close approach with a planet like the Earth, are tidally pulled into two (or more) fragments. The components of these asteroids can experience three possible fates: (a) escape from one another, (b) collision with one another (or no effect), or (c) they can begin orbiting one another. Thus, according to this hypothesis, planetary tidal forces could produce asteroid satellites by a process similar to that which fragmented P/Shoemaker–Levy-9, although in the case of P/Shoemaker–Levy-9 the comet's 20+ fragments were dispersed into an unbound cluster due to its very close encounter (1.3 Jupiter radii) with Jupiter. This hypothesis differs from previous work in that it no longer treats rubble-pile asteroids as an endstate or a sink, but rather as a potential source for binary asteroids; it is no longer required that all binaries encountering Earth be a by-product of asteroid collisions within the main asteroid belt (e.g., analogous to Ida and Dactyl).

Are contact-binaries a reasonable approximation for rubble-piles undergoing a close approach to the Earth? To first order, the answer is yes: Recent work by Asphaug and Benz (1996) and D. Richardson (personal communication), who used N-body codes (with self-gravity and collisions) to model the tidal elongation of rubble-pile asteroids and comets encountering planets, found that rubble-pile asteroids often undergo "mass stripping," (small fragments are created or ejected) or "tidal fission," (similar sized components are created) during close encounters with the Earth. The following characteristics were found to be conducive to producing mass stripping or tidal fission (D. Richardson, personal communication): (a) a fast prograde rotation rate (near the critical breakup limit), (b) an elongated shape (mass is more readily shed from the ends of the asteroid, (c) periapse distance close to Earth, (d) low encounter velocities, and (e) low bulk density. Orientation of the elongated body was also critical to determining the outcome of the encounter. (For more information, see Boss *et al.* (1991) for an excellent review of the processes involved with tidal disruption and an upcoming paper by Richardson, Bottke, and Love.)

How do tidal forces break up rubble-pile asteroids when they encounter a planet? Here we provide a brief description of the processes seen in the N-body models:

A non-rotating spherical rubble pile asteroid, made up of a large number of equal sized spherical fragments, has an equipotential surface which follows the shape of the object. This surface is modified into an oblate spheroid as it approaches Earth, with the ends of this spheroidal surface pointing toward the center of the Earth (in some cases, it can become cylindrical or needle-like). Near closest approach with Earth, the ends of this surface are open ended. Particles finding themselves outside the new shape of the equipotential surface act like rocks on the steep slope of a mountain during an earthquake; they roll over one another "downhill" to fill in the valleys near the ends of the equipotential surface. However, friction prevents them from moving instantaneously and a fraction of the energy transferred from the Earth is dissipated as heat in inter-particle collisions. As the system moves beyond closest approach with Earth, the particles are unable to catch up to the changing shape of the equipotential surface pointing toward Earth's center; the particles' new trajectories are affected by shifting planetary torques and keplerian shear (bodies close to Earth move faster than those further away) as well, which may place the objects into mutual orbits with one another. As the fragments move even further away from Earth, gravitational instabilities may clump together nearby particles into one, two, or more clusters, depending on the nature of the encounter. The primary, if left more or less intact, may take on an ellipsoidal shape. In other encounters, where planetary tidal forces are less effective, fragments may be stripped off near the end of the elongated primary. It has been suggested that planetary encounters may, in fact, be responsible for the elongated shape of many near-Earth asteroids (Solem and Hills 1996). If the sphere has an initially prograde rotation (relative to the planetary encounter trajectory) it may more readily undergo mass-stripping and SL9-type events (prograde rotation), though an initial retrograde rotation will discourage such events.

If more than two clusters become gravitationally bound to one another, or if several fragments are stripped off the primary, the multiple-body system evolves like a star cluster, where the most stable endstate would be a binary system (Binney and Tremaine 1987). Extra fragments would either collide with a bound cluster or escape. Asphaug and Benz (1996) suggest that the apparent disruption of one of P/Shoemaker–Levy-9's fragments several months prior to its impact with Jupiter may have been the result of several gravitationally bound clusters escaping one another. Thus, we can expect that rubble-piles and contact binaries should yield similar outcome statistics.

Finally, we note that the amount of mass stripped off the rubble-pile asteroid does not have to be large; two of the three doublet craters on Earth have 10 : 1 diameter ratios, which translates into a 1000 : 1 volume ratio. Moreover, if several fragments are stripped off the primary during the same encounter, the probability that one of those objects will end up orbiting the primary is enhanced.

IV.B. Model of Contact-Binaries Encountering Earth

To test our hypothesis, we modeled close encounters between loosely bound contact-binary asteroids and the Earth using an adaptive fifth order Runge–Kutta numerical integrator (Press *et al.* 1986). Our model's assumptions, which used the work of Melosh and Stansberry (1991) as a starting point, are summarized here:

The coordinate system for the encounter was defined in terms of the vector distance between the center of the planet and the center of mass between the binary components (**R**) and the relative separation distance between the components (**r**). Solving for the equations of motion, Melosh and Stansberry (1991) determined five degrees of freedom, two describing the hyperbolic motion of the binary's center of mass encountering the planet (the "encounter" equations of motion), and three describing the relative motion of the two components around one another (the "orbital" equations of motion). Tidal perturbations between the planet and the components were explicitly calculated. Additional details on their equations of motion and their integration procedure can be found in their paper.

To account for the contact-binary's new close approach trajectory near the planet, we modified their Eq. 9 to account for close planetary approaches

$$\frac{d\Omega(0)}{dt} = \pm\frac{d}{R^2(0)}\sqrt{V_\infty^2 + \frac{2GM_{\mathrm{PL}}}{d}}, \tag{1}$$

where $R(0)$ is the initial distance between the center of mass of the contact-binary and the center of Earth, $\Omega(0)$ is the initial angle between $R(0)$ and the x-axis of the encounter plane, M_{PL} is the mass of the planet, V_∞ is their relative encounter velocity "at infinity," and d is the close approach distance in terms of the impact parameter b:

$$d = \frac{-GM_{\mathrm{PL}}}{V_\infty^2} + \sqrt{\left(\frac{GM_{\mathrm{PL}}}{V_\infty^2}\right)^2 + b^2}. \tag{2}$$

Initial conditions for the contact-binary asteroids were idealized as a set of spheres of radii $R_1 = 1$ km and $R_2 = 0.5$ km, with density 2600 kg/m^3. The spheres follow circular orbits around their mutual center of mass, touching at one point. These parameters yield an initial rotation period of 3.55 hours. The components were numerically modeled as point masses; to prevent them from approaching closer than their physical diameters, a restoring force (repulsive potential) was activated whenever the components intersected one another. Additional terms were included to the restoring force to equilbrate spin and angular momentum during the time the components were in contact.

The contact-binaries were started far from the Earth at a distance of 60 Earth radii. Each binary was given a relative encounter velocity V_∞, a close approach distance d, and a random initial orientation. The outcome of each encounter was found by calculating the mutual orbital energy and angular momentum of the components after the center of mass of the contact-binary components had receded 60 Earth radii from the Earth. If the components' mutual orbital energy was greater or equal to zero, the outcome was scored as "escaped" (i.e., unbound mutual orbits). If

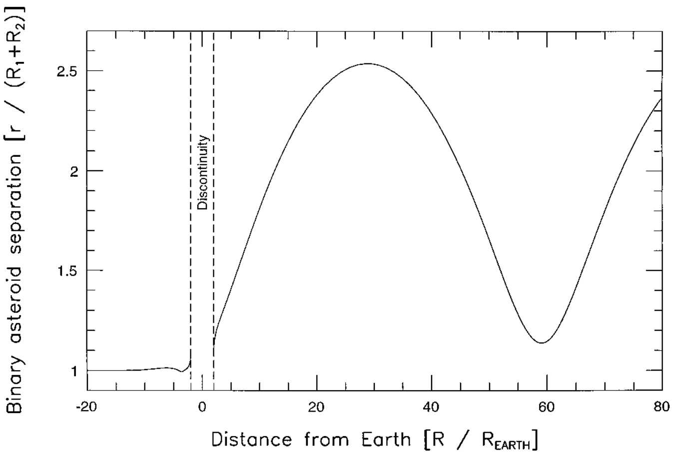

FIG. 1. Encounter between a contact binary (0.5 and 1 km in radius with a rotation period of 3.55 hr, and a density of 2600 kg/m^3) and the Earth. The encounter velocity was $V_\infty = 12$ km/s and the close approach distance $d = 2$ Earth radii. The ordinate shows the change in separation distance r (in terms of the sum of the radii of the components). The abscissa is the distance from the Earth in Earth radii. A discontinuity exists from -2.0 to 2.0 Earth radii (see text). Their final mutual semimajor axis and eccentricity after encounter are ~2.8 km and ~0.38, respectively.

their mutual orbital energy was negative (bound), tidal forces were not strong enough to disassociate the pair. Using the orbital energy and angular momentum equations to find the component's mutual semimajor axis (a_{PAIR}), mutual eccentricity (e_{PAIR}), and mutual perihelion, we determined whether a collision had/would occur, whether the objects had remained in contact throughout the encounter, or whether the objects were in orbit around one another.

IV.C. Single Encounter between a Contact-Binary and the Earth

To demonstrate how this model works, we simulated an encounter between a single contact-binary asteroid and the Earth. We chose its relative encounter velocity V_∞ to be 12 km/sec (the mean encounter velocity of near-Earth asteroids with Earth (Bottke *et al.* 1994b) and its planetary close approach distance d to be 2.0 Earth radii. Figure 1 shows the change in separation distance r (relative to the sum of the component's radii) vs the distance of the contact-binary's center of mass from Earth. (Note that since the contact-binary never approaches within 2.0 Earth radii of Earth, Fig. 1 shows a "discontinuity" from -2.0 Earth radii to 2.0 Earth radii.) We find that the components are pulled apart by the Earth's tidal forces prior to closest approach with the Earth, causing them to recollide once. Then, near closest approach, the components are pulled apart again, this time to a much greater extent. However, for this case, Earth's gravitational forces are not strong enough to pull the components into unbound trajectories; instead, these components begin to orbit one another. Their final mutual semimajor axis after encounter is ~2.8 km (1.83 times the mean diameter of the objects), while their final mutual eccentricity ~0.38. Thus, this orbit is stable since the objects do not pass close enough to collide with one another (i.e., their perihelion is 1.7 km) and dissipative effects (tides between the components) are not taken into account.

IV.D. Post-encounter Outcome Statistics for Contact-Binaries Encountering Earth

When we run the previous test case with the same values of V_∞ and d but with different initial orientations of the contact-binary components, we find a variety of different outcomes (i.e., collision between the components or no effect, escape of the components, or a detached binary with different values of their mutual semimajor axis and eccentricity). Thus, by running our model with thousands of contact-binaries, each with a randomly chosen initial orientation, we generate outcome statistics which tell us whether typical close encounters between rubble-pile asteroids and the Earth produce asteroid satellites.

Figure 2 shows the post-encounter statistics for contact-binary asteroids encountering the Earth at low (4 km/sec), moderate (12 km/sec), and high (20 km/sec) values of V_∞. For each velocity, we tabulated the encounter outcomes from 10,000 contact-binary asteroid runs at each value of d (d = 1.5–10.0 Earth radii, incremented by 0.5 Earth radii) and plotted those outcomes as a percentage, where all the outcomes added together equal 100%. If an orbiting outcome was obtained, we stored both its mutual semimajor axis and eccentricity. These stored values will be discussed in the next section.

For the low velocity case (4 km/sec), we found that over half the contact binary components escape one another at close approach distances less than 2 Earth radii, and that less than 10% end up in oribit around one another. As d increases, the percentage of escape outcomes decreases, demonstrating that planetary tidal forces weaken as we move away from the planet (i.e., they drop off as 1/distance^3). However, for most contact-binaries, the most likely outcome is collision or no net effect between the components (a collision outcome implies the components separated during the encounter but subsequently collided and continued on as a contact binary). For high values of d, the contact-binaries do not separate at all.

For the moderate and high velocity case (12; 20 km/sec), we found that a lower percentage of contact binary components escape one another at low Earth radii. Conversely, a larger percentage of contact binaries go into stable orbits around one another than before. Higher velocity encounters mean that the contact binaries spend less time in proximity of the Earth, which in turn means that

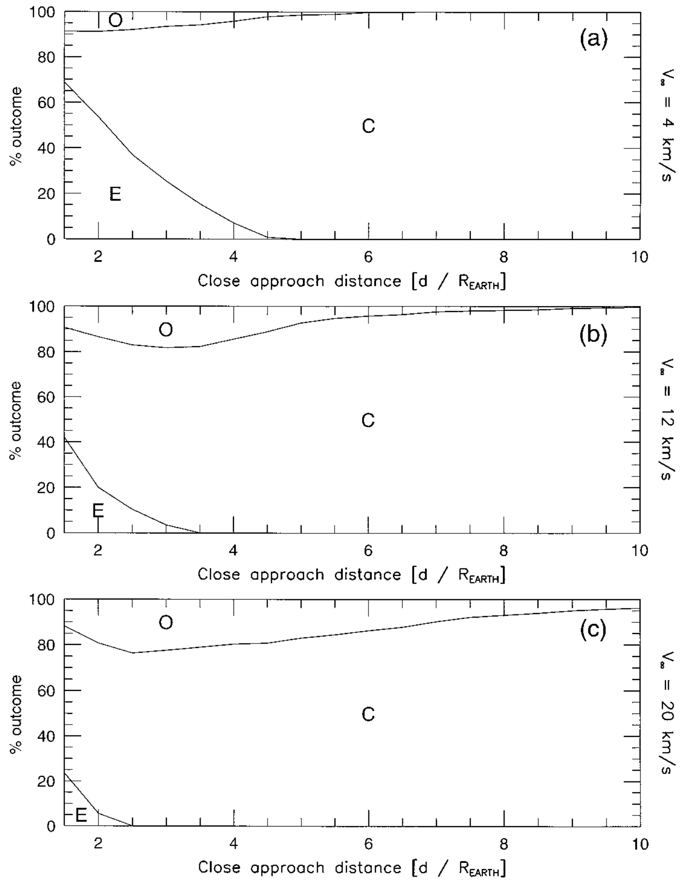

FIG. 2. Post-encounter statistics for spherical contact-binaries encountering the Earth at encounter velocity V_∞ of 4 (a), 12 (b), and 20 km/s (c) over various closest approach distances *d*. Ten thousand random initial orientations were used for each choice of the encounter velocity V_∞ and the close approach distance *d*. The three encounter outcomes, (E) components escaping one another, (C) components colliding with one another or no effect from planetary tides, and (O) components orbiting one another, were tabulated and plotted as a percentage relative to *d*, where all the outcomes added together equal 100%.

planetary tidal forces have less time to pull the components apart, resulting in more orbiting cases and fewer escapes.

The size and shape of the orbit of each binary asteroid after encounter is shown in Fig. 3, where we plot the median mutual semimajor axes and eccentricity for the orbiting outcomes of Fig. 2 over our chosen values of *d* and V_∞. A few pairs in our sample have anonymously large semimajor axes, increasing the mean relative to the median (e.g., for 2.0 Earth radii, the median value is 2.9 mean diameters while the mean value is 11.1 mean diameters out of 873 orbiting pairs). The median and mean eccentricity values are much closer to one another (e.g., the median value is 0.44 while the mean value is 0.46). Note that solar tides would cause orbiting pairs separated by a distance larger than half their mutual Hill sphere to escape one another (see Section V.C). Higher encounter velocities result in low median semimajor axes values, showing again that fast planetary encounters do not leave much time for planetary tidal forces to pull the asteroids apart.

Finally, we find that most contact-binaries do not achieve significant enough separation after a single encounter with Earth to form doublet craters; separation distances on the order of 10 times the sum of the components radii are needed to form two distinct craters (see Section VI.B). Thus, an additional separation mechanism is needed to produce doublet craters.

IV.E. Post-encounter Outcome Statistics for Binary Asteroids Encountering Earth

We also tested well-separated binary asteroids (components separated by a few times their mean diameter) encountering the Earth instead of contact-binaries. Figure 4 shows the post-encounter outcome statistics for 10,000 binary asteroids encountering the Earth with initial semimajor axes values of 4.0 times the sum of their radii (6

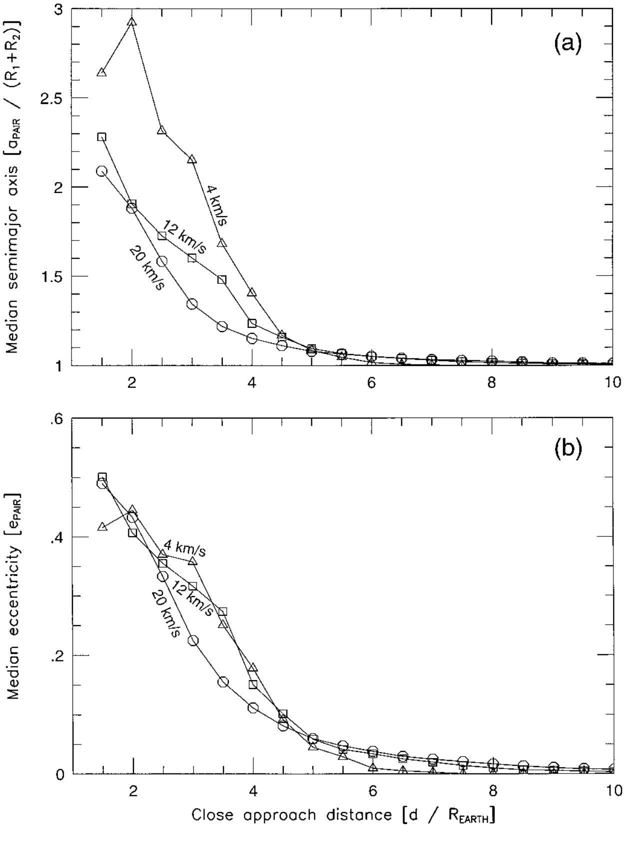

FIG. 3. Post-encounter outcome statistics for all orbiting endstates from Fig. 2 (V_∞ of 4, 12, and 20 km/sec). The median values for the binary's mutual semimajor axis (Fig. 2a) and eccentricity (Fig. 2b) are plotted for various values of the close approach distance *d*.

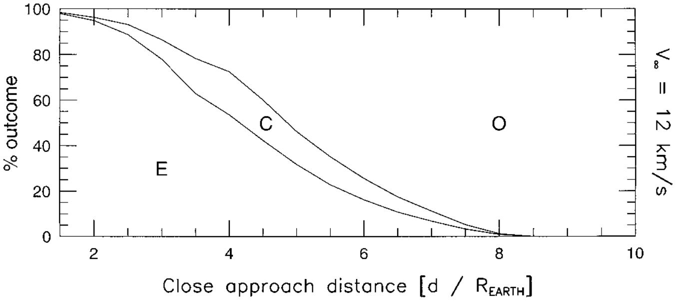

FIG. 4. Post-encounter statistics for binary asteroids encountering the Earth at encounter velocity $V_\infty = 12$ km/sec over various closest approach distances *d*. The initial mutual semimajor axis for each binary was 4.0 times the sum of the radii of the components, while the initial mutual eccentricity was 0.0. Outcomes are displayed in the same format as Fig. 2.

km), initial mutual eccentricities of 0.0, and an encounter velocity of 12 km/sec over a range of *d* values (1.5 through 10.0 Earth radii, incrementing by 0.5 Earth radii). We find that binary asteroids are far more susceptible to planetary tidal forces than contact-binaries, with escape outcomes resulting for nearly all close encounters. In addition, encounters as far away as ~8.5 Earth radii can still cause these binary components to escape from one another. Collision outcomes tend to occur infrequently, since the binary components are small targets compared with the volume their orbit displaces. The binaries that remain in orbit around each other tend to have increased mutual semimajor axes (median of 5.8 mean diameters) and increased mutual eccentricities (median of 0.57).

We have also generated outcome statistics for binaries encountering the Earth over a range of varying parameters, though for brevity we only report the general tendencies of these runs. If we increase the initial mutual semimajor axes of the binaries, we find that escape outcomes occur more frequently for a given value of *d*. If we start with binaries on mutually eccentric orbits, we find slightly more escape and collision outcomes than with binaries on mutually circular orbits. We speculate that the increase in escape outcomes may be produced by eccentric binaries encountering Earth near their own mutual orbit's aphelion, where the pair of objects spend the most time and where the bond between the pair is weakest. The increase in collision outcomes may be produced by eccentric binaries encountering Earth near their own mutual orbit's perihelion, where perturbations could effectively decrease the volume of space over which collisions can occur. Neither trend significantly changes the outcome statistics found using binaries with circular orbits.

Our numerical results are in good agreement with the results of Chauvineau *et al.* (1991), Farinella (1992), and Farinella and Chauvineau (1993), who derived approximate analytical expressions to determine the outcome of binary asteroids encountering the Earth. They found that the change in the binary's orbital energy (E) and angular momentum (L) after a close approach with Earth is

$$\frac{\Delta E}{m} \approx \frac{GM_\oplus n r^2}{V_\infty b^2} \tag{3}$$

(n is the binary's mutual mean motion, r is the separation distance between the components ($\equiv a_{\mathrm{PAIR}}$), $M_\oplus$ is the mass of the Earth, and m is the mass of both binary components), and

$$\left|\frac{\Delta L}{L}\right| \approx \left|\frac{\Delta E}{2E}\right|. \tag{4}$$

By introducing gravitational acceleration $g = (GM_\oplus/R_\oplus^2)$ into (3), one can find the ratio between the specific energy change of the binary per encounter and the binary's binding energy ($n^2 a_{\mathrm{PAIR}}^2/2$):

$$\text{Energy Ratio} = \left(\frac{2g}{nV_\infty}\right)\left(\frac{R_\oplus^2}{b^2}\right). \tag{5}$$

Equation 5 shows that encounters with small V_∞ and b (which translates into d) are the most effective, and binaries with small n (i.e., large semimajor axis) are the least bound to one another. It also shows that decreasing b by a factor 2 is approximately equivalent to decreasing V_∞ by a factor 4 or the mutual semimajor axis of the components by a factor 2.8, which is in good agreement with our results. For escape encounters (i.e., energy ratio >1.0), Eq. 5 predicts the limiting close approach distance can't be much larger than ~5 Earth radii, roughly the same value we find.

IV.F. Implications

We conclude from these runs that Earth's tidal forces can cause the components of contact-binary asteroids and rubble-pile asteroids to orbit one another. However, since orbiting pairs are less gravitationally bound to one another than contact binaries, they are also more susceptible to the influence of planetary tides, which greatly increases the likelihood of the components escaping one another. Since close approaches with Earth (i.e., within a few Earth radii of the center of the planet) are much more probable than direct impact encounters, asteroid satellites, whether produced by tidal forces or by catastrophic collisions in the main-belt, are nearly always stripped from their primary during close approaches by Earth's tidal forces. Thus, if contact-binary asteroids only produce a satellite from planetary tidal forces, once over their entire history, few (if any) doublet craters would be formed on the terrestrial planets.

However, rubble-pile asteroids have the potential to produce an asteroid satellite each time they have a close encounter with the Earth, conceivably replacing any satellite lost during a previous (or the same) encounter. As long as a rubble-pile maintains sufficient mass and fragments to continue forming two primary components, tidal fission may occur multiple times over its lifetime. The size at which a rubble-pile asteroid becomes unable to form a binary is not presently known, but the record of doublet splotches on Venus indicates that binary components can be as small as a few hundred meters in diameter. It may even be possible for both components of a binary asteroid to undergo tidal disruption/fission during the same planetary encounter, though it is hard to imagine how such a system could be stable unless the pairs were widely separated.

One further implication is that these encounters may also induce a faster or slower rotation on the contact-binary, making them more or less susceptible to breakup or mass stripping during a close planetary encounter (Boss *et al.* 1991, A. Harris, D. Richardson, personal communication). Thus, asteroids with slow rotation periods (e.g, Toutatis) may not be an endstate in our scenario; if a close encounter increases their rotation rate, they may undergo tidal fission or mass stripping during a later encounter. However, this effect probably cannot be modeled accurately using two bodies (D. Richardson, personal communication); a more detailed treatment requires an N-body code and is beyond the scope of this paper.

V. HOW MANY EARTH-CROSSING ASTEROIDS HAVE SATELLITES?

V.A. Monte Carlo Model of Rubble-Pile Asteroids Making Multiple Encounters with Earth

The previous study of single encounters between binary asteroids and the Earth shows that planetary tidal forces can produce asteroid satellites from rubble-pile asteroids, though the separation distance between the components after a single encounter is almost always too small to form a doublet crater. However, most Earth-crossing asteroids make multiple encounters with Earth before impacting a terrestrial planet. In addition, binary asteroids are susceptible to small perturbations from distant Earth encounters and mutual tidal forces, which may increase their mutual separation distance. Thus, to estimate the steady-state population of well-separated binary asteroids in the Earth-crossing asteroid region, we combined our numerical model of planetary encounters with a Monte Carlo code based the work of Chauvineau *et al.* (1995) that computes the frequency and characteristics of asteroids making repeated encounters with Earth. This model also includes the effect of mutual tides on the components between planetary encounters using statistical methods. We provide a brief summary of the Monte Carlo methodology used by Chauvineau *et al.*, with a description of our modifications.

First of all, we chose the rubble-pile's encounter velocity V_∞ using a probability distribution for asteroid velocities at Earth encounter based the actual orbits of Earth-crossing asteroids (Bottke *et al.* 1994b). Next, we estimated the maximum distance at which a planetary encounter significantly modifies a binary asteroid's orbital energy using Chauvineau *et al.*'s criteria for a "close" encounter

$$b_2 = \frac{V_\infty}{n}, \tag{6}$$

where n is the binary's mutual mean motion. However, our numerical results suggested that their value of b_2 was underestimated for well-separated binaries; we found that particular binary orientations at encounter with the Earth could lead to small but significant changes in the binary's orbital energy. Thus, to ensure we did not miss any of these important encounters, we increased b_2 by a factor of 2–10. (Theory suggests that important tidal effects can occur for $b_2 \leq 9\ V_\infty/n$, on the grounds that prograde satellites are stable for orbital periods up to ~1/9 that of their primary.)

The probability of a asteroid encountering Earth within the distance b_2 and within timestep δt was estimated by Chauvineau *et al.* to be

$$P_{\mathrm{ENC}} = \left(\frac{\delta t}{\tau_{\mathrm{COLL}}}\right)\left(\frac{b_2^2}{2R_\oplus^2}\right), \tag{7}$$

where τ_{COLL} is on the order of 100 Myr, the typical lifetime of near-Earth asteroids against collisions with the terrestrial planets (Bottke *et al.* 1994b). The timestep δt was chosen to be far shorter than τ_{COLL} (δt = 1000 years). To determine whether an encounter had occurred, a random deviate between (0, 1) was chosen and compared with P_{ENC}. If the random deviate was less than P_{ENC}, the value of the impact parameter was chosen randomly over the interval (0, b_2) according to the probability density:

$$p_b db = \frac{2bdb}{b_2^2}. \tag{8}$$

With the impact parameter b and encounter velocity V_∞ chosen, the mutual orbital parameters of the contact-binary or binary asteroid were passed to the numerical model described in Section IV, which tracked the effects of planetary tidal forces at encounter.

In the interim between Earth encounters, mutual tidal forces, which exchange rotational and orbital angular momentum between the binary components (if binary components exist), can modify the binary's mutual semimajor axis, eccentricity, inclination, and spin state. Our model of mutual tidal evolution is the same as that described by Weidenschilling *et al.* (1989) and updated in Chauvineau *et al.* (1995) (For brevity, we do not write their tidal expressions here). As they do, we make the simplifying assumption that the mutual inclination is unaffected by tides and the rotational angular momentum of the smaller binary component is negligible. This treatment is probably adequate for a statistical study, but any detailed investigation of a single binary asteroid should use a more sophisticated tidal evolution model (MacDonald 1964, McCord 1966).

We caution that, by definition, this method is approximate and produces planetary encounter timescales which are almost certainly inaccurate when small perturbations are important. We hope that future models with more capable computers will use numerical integration techniques to treat the complete dynamical evolution of rubble-pile asteroids in the terrestrial planet region.

V.B. Sample Monte Carlo Run

The evolution of rubble-pile asteroids (that we approximate using contact-binaries) in our Monte Carlo model can be described as follows. We start with loosely bound rubble-pile asteroids, which change little until they undergo a close encounter with Earth (note that encounters only occur with the Earth; this particular code has no ability to scatter asteroids from one planet to another). As described previously, a close encounter causes a rubble-pile to undergo mass stripping or tidal fission, causing the primary to evolve into two components which may either collide with one another (or no effect), escape one another, or go into orbit around one another. If the components collide with one another, they remain in our code to undergo another planetary encounter at a later time. If the components escape from one another, we still consider the primary component a rubble-pile, so it remains in our code to possibly form a new satellite. If the components begin to orbit one another, distant planetary encounters and mutual tidal effects become important. Most of the contact binaries tested in our model go through this contact-orbit-escape sequence multiple times over 100 Myr. Thus, by combining results from lots of test cases, we should be able to predict the steady-state number of binary asteroids among the Earth-crossing asteroid population.

Figure 5 shows a simulation of the evolution of a binary asteroid's mutual orbital parameters vs time. The largest "jumps" in the curves are due to close Earth encounters. Smaller jumps occur at more distant encounters, while more gradual changes are induced by mutual tides. Some of these modifications can lead to collision or escape between the components, but, on average, we see that the semimajor axis and eccentricity between the components increases with time through a random walk process.

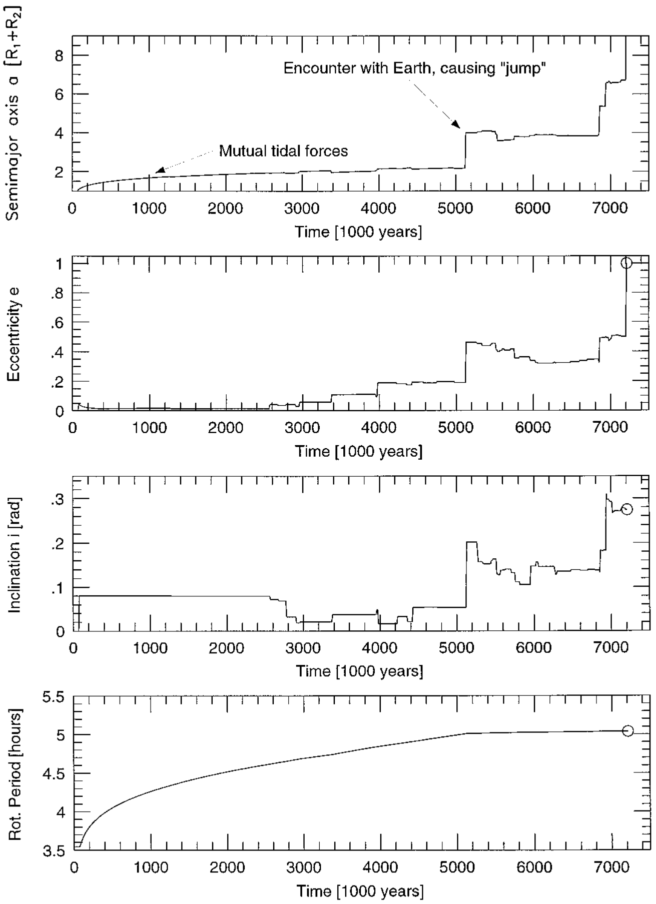

FIG. 5. Evolution of a binary asteroid in our Monte Carlo code. We plot the binary's mutual semimajor axis, eccentricity, inclination, and rotation period of the primary component vs evolution time. The jumps in the curves are due to perturbations from planetary close approaches while the more smooth increases/decreases are from mutual tides. Note the random walk increases in the separation distance between the binary components before a close Earth approach causes the two components to escape one another.

Eventually though, as discussed in Section IV.F., most binary asteroids make another close approach to the Earth before impact, which usually strips the primary component of its satellite. However, as before, the primary component remains a rubble-pile, which can form a new satellite during a subsequent close approach. A few eventually may approach close enough to impact the Earth; if one of these few is a well-separated binary, it may produce a doublet crater.

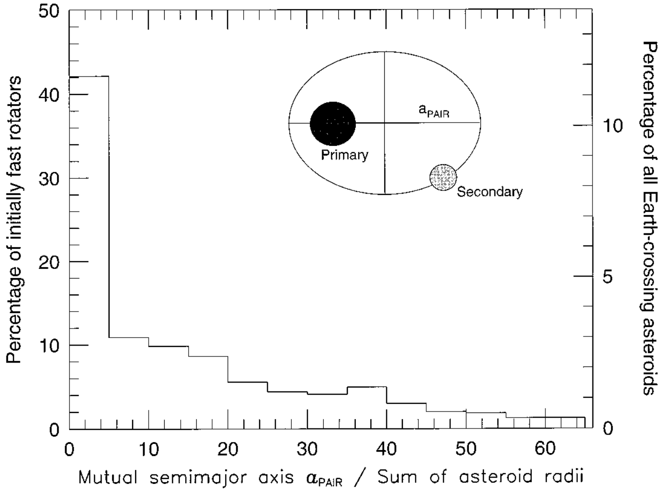

FIG. 6. The steady-state distribution of co-orbiting asteroids in the Earth-crossing region. The ordinate on the left side of the plot shows the percentage of objects starting with this 3.55 hr rotation period that evolve into binary asteroids, while the abscissa shows their mutual semimajor axis (in units of the sum of the radii of the components). Our results show that our starting asteroid population evolves into a population where over half are binaries, some separated by large distances. The mutual eccentricities of those binaries tend to be small (most orbit each other on nearly circular orbits). The ordinate on the right side of the plot shows the percentage of the km-sized ECAs that should have satellites (~15%). We obtain this percentage by scaling our results by the actual fraction of ECAs with short rotation periods (~28% with rotation periods <5.5 hr; see text for details).

V.C. Steady-State Distribution of Binary Asteroids in the Earth-Crossing Region

The Monte Carlo model can predict the steady-state distribution of well-separated binary asteroids in the Earth-crossing asteroid region. We started 90 contact-binaries in our model over ten different encounter velocities (V_∞ from 2 km/sec to 38 km/sec, incremented by 4 km/sec). We considered an asteroid satellite's orbit stable if it matched criteria found by Hamilton and Burns (1991) (see also Zhang and Innanen 1988): Asteroid satellites on initially circular prograde orbits are stable up to half a Hill sphere (see the definition of a Hill sphere in Roy 1988), while satellites on initially circular retrograde orbits are stable throughout the Hill sphere. In this case, a prograde orbit is defined as one where the satellite's angular velocity around the primary is in the same sense as the primary's angular velocity around the Sun; a retrograde orbit is defined as one where the satellite's angular velocity has the opposite sense. For simplicity, we use the lower limit: for the component parameters used in our model (density of 2600 kg/m^3), one-half a Hill radius at 1.0 AU is ~60 mean diameters ($R_1 + R_2$).

Our results are shown in Fig. 6. We find that a population of weakly bound rubble-piles with short rotation periods evolves into a population where over half are binary asteroids (~57%), some separated by large distances that are limited only by solar tides. Though such results are encouraging, such a binary population would create many more doublet craters on the terrestrial planets than allowed by observations. However, this estimate only applies to Earth-crossing asteroids with fast rotation rates; many Earth-crossers are slow rotators with rotation periods longer than ~6 hr, making them difficult to pull apart by Earth's tidal forces (D. Richardson, personal communication). To estimate the fraction of Earth-crossers with short rotation periods, we modeled their rotation period distribution as a Maxwellian distribution with a mean period of 6 hr (A. Harris, personal communication; see also Lagerkvist and Claesson 1996). We scaled this distribution to account for the ~20% of Earth-crossing asteroids with very long rotation periods (e.g., 4179 Toutatis has a complex "tumbling" rotation period between 5–7 days; Hudson and Ostro 1995) and for the paucity of rotation periods shorter than 3.55 hr. We find that only ~28% of all Earth-crossing asteroids have rotation periods <5.5 hr, implying that we must scale our steady-state binary asteroid distribution results by this fraction as well.

Scaling the fraction of well-separated binary asteroids in Fig. 6 (~57%) by the fraction of fast rotating Earth-crossers (~28%), we can conclude that ~15% of the km-sized Earth-crossing asteroids should have satellites generated by Earth's tidal forces, and that this steady-state population also described the population that impacts Earth.

VI. FORMING DOUBLET CRATERS ON THE TERRESTRIAL PLANETS

VI.A. Model of Binary Asteroids Impacting Earth

Now that we have characterized the population of Earth-crossing asteroids with satellites, we address the question of how many of those binaries produce doublet craters at impact. To do that, we modified the model of Melosh and Stansberry (1991) to track binary asteroids on impact encounters with the Earth. The details of this model are given in Melosh and Stansberry (1991) and in Section IV. This model accounts for Earth's tidal perturbations before impact, the trajectory and velocity of the components near the planet, and the component's orientation at impact. The last factor is critical, since it determines whether these bodies form doublet craters rather than single craters. For example, a well-separated binary asteroid in space may impact a planet such that its components fall on top of one another; in that case, no doublet crater would be formed.

To generate outcome statistics, we started 10,000 binary asteroids (same sizes, densities reported in Section IV) at a distance of 60 Earth radii from Earth, each with a random initial orientation, a chosen separation distance between binary components on circular orbits (from a mutual semi-

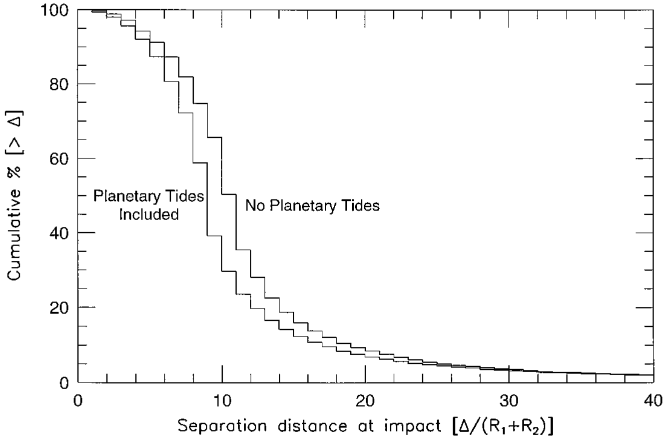

FIG. 7. Separation distance between the components of binary asteroids impacting the Earth. We started with 10,000 binary asteroids, initially separated by 10 times the sum of their component radii, which encounter Earth at velocity $V_\infty = 12$ km/sec. The top histogram shows the cumulative percentage of binaries impacting the Earth separated by a given distance or smaller (in units of the sum of components radii) if planetary tides are neglected. The bottom histogram includes planetary tides. We find that planetary tides (on average) decrease the separation distance between binary components at impact.

major axis of 2.5 mean diameters representing the lowest bin, to 62.5 mean diameters, representing the highest bin; incremented by 5 mean diameters) and a chosen encounter velocity V_∞ (from 2 km/sec to 38 km/sec, incremented by 4 km/sec). The choice of circular orbits for these binaries is reasonable, given that the mutual eccentrivity for most binaries represented in Fig. 6 is less than 0.1. The impact parameter b was selected from a properly weighted random distribution (bdb within the gravitational radius of Earth). The binaries impact the Earth when their mutual center of mass approaches within 1 Earth radius. The separation distance between the components at impact was found by extrapolating each component's trajectory forward or backward to the planetary surface and calculating the separation along the surface (ignoring the curvature of the planet, which is negligible in most circumstances).

Figure 7 shows a sample representation of our results. For this case only, to ease interpretation, we chose binary asteroids initially separated by 10 mean diameters to encounter Earth at $V_\infty = 12$ km/sec. To assess the effect of planetary tides, we removed them from the upper histogram, and included them in the lower histogram. Our results are somewhat surprising, since they indicate that planetary tides (on average) decrease the separation distance between binary components at impact.

Why do planetary tides prevent well-separated binary asteroids from forming doublet craters? Figure 8 shows that while the differential gravitational pull of planetary tides increases the separation distance between the binary components before impact, they also tend to align the impact trajectories of the components, such that the components are more likely to impact near one another or fall on top of one another. Thus, binary components (on average) need an even larger initial separation distance to produce a doublet crater at impact. This result also explains why asteroids pulled apart just before impact rarely produce doublet craters (Melosh and Stansberry 1991); components separated by tidal forces do not tend to move apart in a direction tangential to the surface of the planet.

The results shown in Fig. 8 can also be explained analytically, using the expression of tidal force **T**

$$\mathbf{T} = \frac{3(\mathbf{u}\cdot\mathbf{r})\mathbf{u} - \mathbf{r}}{R^3}, \tag{9}$$

where **r** is vector joining the binary's components, **R** is the vector joining the planet to the binary center of mass, and **u** is the unit vector in the direction of **R** ($\mathbf{R} = R\mathbf{u}$). This equation shows that $\mathbf{T}\cdot\mathbf{r} > 0$ when **r** is aligned with **R**, and $\mathbf{T}\cdot\mathbf{r} < 0$ when these vectors are orthogonal.

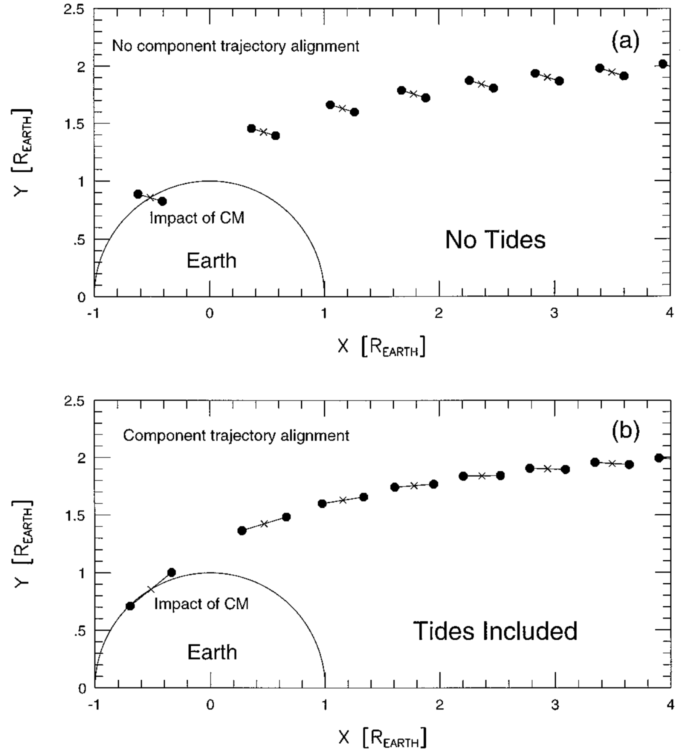

FIG. 8. Sample run showing a binary asteroid impacting the Earth. For this test case, the sizes of the components are $R_1 = R_2 = 1$ km (represented by the dots), and their center of mass at each timestep is represented by the x. Their mutual separation distance has scaled-up by a factor of 100 in this plot so their relative positions and trajectories can be seen. In (a), planetary tides have been neglected; in (b), planetary tides have been included. Note that the inclusion of planetary tides aligns the trajectories of the components such that they impact nearer to one another than the components in (a).

VI.B. Separation Distance Needed to Make Doublet Craters

Two separated asteroids impacting a planetary surface do not necessarily form two craters. Binary components impacting close to one another may create a single crater, an elongated crater, or a crater with a complex morphology. The only experimental study of the impact morphology of doublet impacts was performed by Oberbeck (1973). Cylindrical projectiles of Lexan plastic were cut longitudinally to a point within 0. 2 mm from the end of the projectile and fired at 2.3 km/sec (with a normal trajectory) into a fine grained quartz sand target. The resulting doublet craters began to lose their identity when the ratio of the separation distance between the impact points (S) over the diameter of one of the craters (D) (using same sized projectiles) reached 0.81. Many of the experimentally-produced doublet craters formed subdued ridges between the craters. Smaller ratios of S/D yielded elliptical craters to single craters: e.g., a S/D ratio of 0.44 yielded an elliptical crater with an interior ridge, a S/D ratio of 0.36 yielded a less elliptical crater with a central peak, and smaller S/D ratios yielded circular flat floored craters with central peaks and ridges. Oberbeck's results imply that some of the interior features of large craters on the Moon, Mercury, and Mars, previously attributed to slumping/collapse of crater walls may, in fact, be from the near-simultaneous impact of two asteroids next to one another.

Since many of the doublet craters on the terrestrial planets have different size components, we choose a more conservative criteria for producing doublets in our model than Oberbeck (1973). We estimate that ratio of the separation distance between the projectiles at impact (Δ) over the sum of the crater radii ($D_1/2 + D_2/2$) must be larger than 1.0 to form a doublet crater. We find the size of each crater (D) using the gravity-scaling laws in Melosh (1989) (see also Schmidt and Housen 1987) for impacts into competent rock or saturated soil

$$D(\text{km}) = 0.301 \left[\frac{V_{\text{IMP}}^2\,(\text{m}^2/\text{s}^2)}{g(\text{m/s}^2)} \right]^{0.22} L^{0.78}(\text{km}), \qquad (10)$$

where g is planetary surface gravity, V_{IMP} is the projectile's velocity at impact, and L is the projectile diameter (for the results shown here, we assume that the impact angle is 45°).

Because g and V_{IMP} varies from planet to planet, the separation distances required to form a doublet crater also varies. For example, spherical binary components with radii 0.5 and 1.0 km radii impacting the Earth (g = 9.8 m/sec^2; mean asteroid impact velocity V_{IMP} = 17.2 km/sec; Bottke *et al.* 1994b) must be separated by 18 km to form a doublet crater, while the same bodies impacting the Moon (g = 1.6 m/sec^2; mean asteroid impact velocity V_{IMP} = 12.6 km/sec; Bottke *et al.* 1994b) must be separated by 23 km. Similarly, doublets formed on Mars (g = 3.7 m/sec^2; mean asteroid impact velocity V_{IMP} = 13.6 km/sec) and Mercury (g = 3.6 m/sec^2; mean asteroid impact velocity V_{IMP} = 30.2 km/sec) require separation distances of 20 km and nearly 30 km, respectively. Thus, to account for these changes, we use Eq. (9) to modify the doublet criterion over each body's specific asteroid impact velocity distribution.

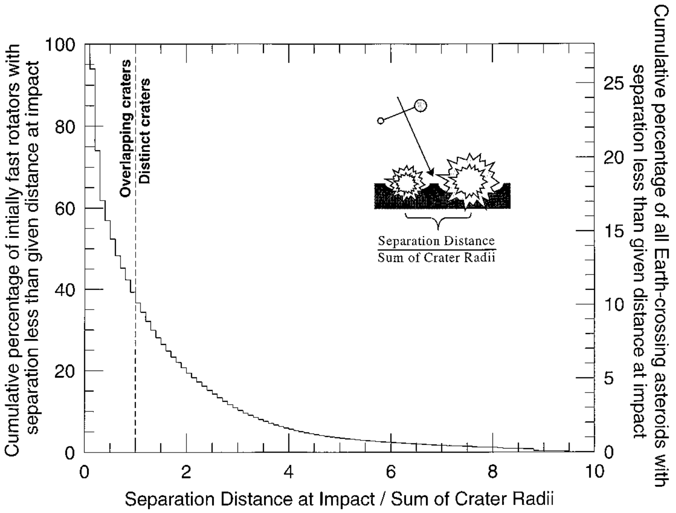

FIG. 9. The fraction of Earth-crossing asteroids (ECAs) impacting Earth that produce doublet craters. The abscissa shows the separation distance between binary asteroid components over the sum of the crater radii found using crater scaling-law results. If the abscissa's value is greater than one, the binary creates a doublet crater. If the value is less than one, the craters overlap one another. The ordinate on the left side of the plot shows the cumulative percentage of objects with 3.55 hr rotation periods which that impact Earth at a given separation distance or smaller. The ordinate on the right side of the plot shows the cumulative percentage of all km-sized ECAs that impact Earth at a given separation distance or smaller. Our results show that ~10% of the ECAs impacting the Earth produce doublet craters, matching observations.

VI.C. The Predicted Doublet Crater Population on the Earth, Moon, and Venus

Folding the results from Fig. 6 into the model described in Section VI.A and applying the crater scaling laws described in Section VI.B, we calculate the fraction of doublet craters formed on Earth (Fig. 9). The abscissa of Fig. 9 shows the separation distance between the binary components over the sum of their crater radii. If the abscissa's value is greater than one, the binary creates a new doublet crater. If the abscissa's value is less than one, the craters overlap one another. The ordinate on the left side of the plot shows the cumulative percentage of objects with 3.55 hr rotation periods which impact Earth at a given separation distance of smaller. We find that if all asteroids are represented by fast rotating loosely bound rubble-piles, nearly 35% of those objects form doublet craters at impact. However, as discussed in Section V.C, less than a third of the Earth-crossing asteroid population are well represented by those initial conditions. Scaling our results by the actual fraction of Earth-crossing asteroids with fast rotation rates (~28%), we find that ~10% of all Earth-crossing asteroids impacting the Earth produce doublet craters, in agreement with observations (Section II.A). This value is smaller than the fraction of well-separated binaries (15%), because planetary tidal forces tend to decrease the separation distance between binaries at impact. However, we caution that doublet statistics on the Earth are poor (3 doublets seen among 28 large craters); the 10% fraction of doublets should only be taken as an indication.

Figure 9 also approximately represents the fraction of doublet craters found on Venus, since its size, density, and its impacting asteroid population, to first order, are the same as Earth's. This result is also consistent with observations (Section II.A).

Somewhat surprisingly, we find that Fig. 9 also provides a good fit to the expected fraction of doublet craters on the Moon. Since the Moon's tidal forces are much smaller than Earth's, a binary asteroid impacting the Moon at a low value of V_∞ undergoes less trajectory alignment among its components (i.e., less likely to fall close or on top of one another—see Section VI.A) than they would experience on a comparable impact encounter with Earth. Thus, binary asteroids impacting the Moon are, on average, more separated at impact than binary asteroids impacting the Earth. This effect decreases for both bodies as V_∞ increases, since planetary tidal forces have less time to perturb and align the components before impact. If this were the only factor, we would expect to find a larger fraction of doublets on the Moon than on Earth. However, from Section VI.B, we find that binaries impacting the Moon, on average, make larger craters than those on Earth, which requires that the components have a greater separation at impact to produce a doublet crater. These two effects roughly cancel one another out, leaving very little difference between Fig. 9 and the curve we found for the Moon. Thus, we predict that ~10% of the impact craters on the Moon should be doublets.

VI.D. The Predicted Doublet Crater Population on Mars

We also modified our Monte Carlo binary asteroid model to determine whether Mars should produce a noticeable signature of doublet craters on its surface. We again start with a population of spherical contact-binaries (0.5 and 1.0 km in radius with a rotation period of 3.55 hr and a density of 2600 kg/m^3) that evolve over multiple passes with Mars (radius of 3395 km, density of Mars of 3900 kg/m^3). Mars's lower density and smaller radius (relative to Earth and Venus) result in a Roche radius half as large as Earth's Roche radius. Thus, asteroids are less likely to be pulled apart at a given distance from Mars than at the same distance from Earth or Venus, assuming all other parameters are the same.

Calculating an appropriate probability distribution of asteroid encounter velocities for Mars is difficult, since the Mars-crossing asteroid population beyond perihelia q = 1.3 AU (the Amor asteroid limit) is not well known. For that reason, we calculated a probability distribution of relative encounter velocities "at infinity" based on close encounters between Mars and Amor asteroids on solely Mars-crossing orbits (140 asteroids as of March 1996, according to Minor Planet Center osculating elements). For calculation details, see Bottke *et al.* 1994b. Thus, we expect that this "best guess" probability distribution is somewhat biased toward larger encounter velocities. This choice should not significantly modify our results, since we do not find large differences in the distribution of separation distances between binary components which encounter Mars at low or high velocities over our chosen evolution time. Our probability distribution showed that most asteroids in our population encounter Mars between 4–8 km/sec (20%), 8–12 km/sec (50%), or 12–16 km/sec (24%). Less than 1.5% encounter Mars at velocities <4 km/sec, and <15% encounter Mars at velocities greater than 18 km/sec.

We ran 90 bodies in our Monte Carlo code for each velocity bin described above. Each asteroid can evolve for as long as 100 Myr, though this value is almost certainly an upper limit; recent results by Gladman *et al.* (1996) show that asteroids entering newly found resonances in the solely Mars-crossing asteroid region can become Earth-crossing much sooner than previously predicted by Arnold-type Monte Carlo models (Arnold 1965). Shortening the evolution time lowers the number of binaries/doublet craters formed in our model. Thus, our results should be seen as upper limits.

We find 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. 10). We find that only ~16% of the fast rotating rubble-piles asteroids that are dominated by Mars-perturbations 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 actually have fast rotation rates (i.e., have less than 5.5 hr rotation periods) (28%), we find that only 4–5% of the asteroids dominated by Mars perturbations become well-separated binary asteroids. In comparison, 15% of the asteroids that encounter Earth become well-separated.

We applied these results to a model of impact encounters between binary asteroids and Mars. Our results show that only ~3% of all of the asteroids that impact Mars form doublet craters (Fig. 11), in agreement with the observations described in Section II.C. If we were to include the results of Gladman *et al.* (1996) and lower our total encounter time, we would find even fewer doublets produced by Mars' tidal forces.

We note that since many near-Earth asteroids are Mars-crossers as well, it could be that some or most of the doublet craters seen on Mars were produced by binary asteroids whose components were initially pulled apart by Earth's (or Venus') tidal forces. To properly account for this factor, one would need to estimate the number of solely Mars-crossing asteroids out of the total Mars-crossing asteroid population, which is beyond the scope of this paper. If, for some reason, the population of solely-Mars-crossers was small compared to the population of Earth-crossing asteroids, we would expect to find the same number of doublets on Mars, Venus, the Moon, and the Earth, since roughly the same population of binaries (produced by Earth and Venus) would impact all four bodies.

These results provide important verification for our scenario describing the origin of doublet craters, since our model can match the fraction of doublet craters found on Venus, Earth, and Mars (the other terrestrial planets have not yet been surveyed quantitatively—see Section II.C). 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 planets (presuming, of course, that the binaries remain bound through numerous planetary close encounters).

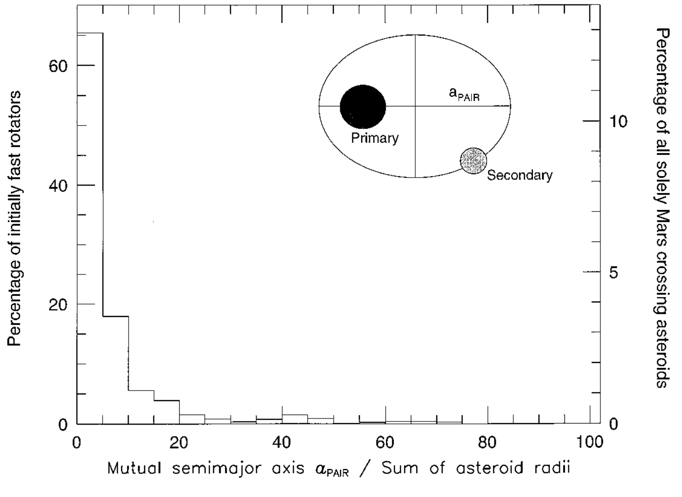

FIG. 10. The steady-state distribution of co-orbiting asteroids in the solely Mars-crossing region. Axes are labeled the same as Fig. 6. Our results show that our starting asteroid population evolves into a population where few are well-separated binaries (relative to results shown in Fig. 6).

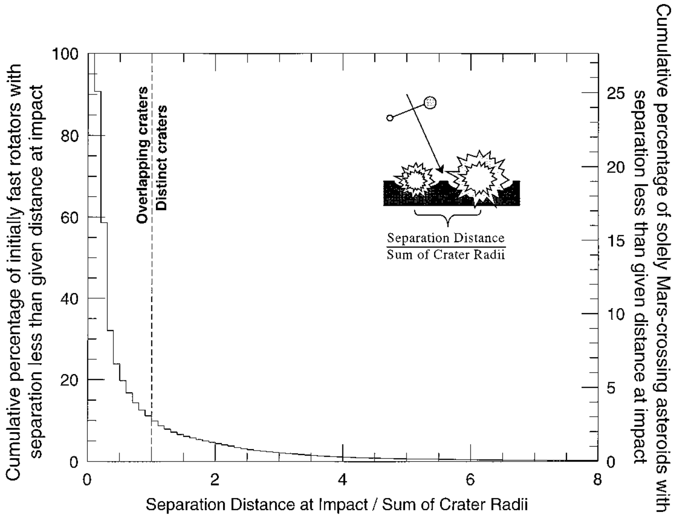

FIG. 11. The fraction of solely Mars-crossing asteroids impacting Mars that produce doublet craters. Axes are labeled the same way as Fig. 9. Only ~3% of these bodies form doublet craters (an upper limit), matching observations.

VI.E. The Predicted Doublet Crater Population on Mercury

To estimate the fraction of doublet craters on Mercury (radius: 2440 km, density: 5440 kg/m^3), we first need to characterize the population of asteroids that impacts Mercury. As of March 1996, there are 24 known asteroids that cross the orbits of Mercury and Earth (according to Minor Planet Center osculating elements). These asteroids have large eccentricities ($e > 0.4$, many with $e \sim 0.8$) and half have large inclinations ($i > 15°$), giving them large encounter velocities with Mercury, Venus, and Earth. No asteroid has yet been found on a solely Mercury crossing orbit.

Since the Roche radii of Earth and Venus are over twice the size of Mercury's, we might expect that the tidal forces of Earth and Venus dominate the tidal evolution of these bodies. However, Mercury's low semimajor axis (0.387) allows it to encounter these asteroids more frequently than Earth or Venus, which conceivably could make a difference. To check this, we calculated the intrinsic collision probabilities and mean encounter velocities of these 24 asteroids with Mercury (P_i = 456 × 10^{-18} km^{-2} yr^{-1}; $\langle V_\infty \rangle$ = 28.6 km/sec), Venus (P_i = 204 × 10^{-18} km^{-2} yr^{-1}; $\langle V_\infty \rangle$ = 24.1 km/sec), and the Earth (P_i = 134 × 10^{-18} km^{-2} yr^{-1}; $\langle V_\infty \rangle$ = 17.5 km/sec), using the technique of Bottke *et al.* (1994b). We then used these values to calculate the relative encounter probability of these 24 asteroids with each planet (including gravitational focussing). We found that these asteroids are nearly 3 times more likely to encounter the Earth than Mercury, and nearly 6 times more likely to encounter either Earth or Venus than Mercury. Thus, if that asteroid population describes the population that impacts Mercury, we would expect that most of the binaries that impact Mercury were formed by the tidal forces of Earth or Venus rather than Mercury.

Can we assume that these 24 asteroids characterize the population of all Mercury-crossers, or is there a large fraction of asteroids on solely Mercury-crossing orbits beyond what we can detect from Earth? To determine the fraction of Mercury-crossers on solely Mercury-crossing orbits, we tracked the collisonal and dynamical evolution of test asteroids in a Arnold-type Monte Carlo dynamical evolution code (Bottke *et al.* 1996). This code accounts for the gravitational perturbations of the planets but not the effect of mean-motion or secular resonances. In the region we are investigating, this approximation provides reasonable qualitative behavior of asteroid evolution, since the dynamical evolution of asteroids with semimajor axes $a < 2$ AU are dominated by planetary close encounters rather than resonance phenomena (Froeschle *et al.* 1996). Simulating the orbital evolution of asteroids removed from the 3 : 1 resonance by planetary perturbations, we started 1000 objects 1 km in diameter with orbital parameters $a = 2.5$ AU, $e = 0.6, 0.65, 0.7, 0.8, 0.9$, and $i = 5°, 10°, 15°, 20°, 25°, 30°$. These objects were allowed to evolve until they collided with a terrestrial planet, were removed from the system by perturbation from Jupiter, or until the bodies and their fragments eroded below a size of 200 m. Our results show that while many asteroids took on orbits consistent with the orbits of the 24 known Mercury-crossers, very few reached solely Mercury-crossing orbits. Thus, we predict that the observed population of Mercury crossers provides a good first order characterization of the population of all Mercury-crossers. (Note that some asteroids in our model reach Mercury- and Venus-crossing orbits but not Earth-crossing orbits. Since this region of space cannot easily be observed from Earth, it is possible we are oversimplifying our problem. However, we do not expect these asteroids to change our results significantly; Venus is roughly the same size and density as the Earth, and the encounter trajectories and velocities for these bodies with Venus is comparable to those of the 24 Mercury-crossing asteroids with Earth.)

To estimate the fraction of doublets formed on Mercury, we first need to find the fraction of Mercury-crossing binary asteroids produced by Earth's (and Venus's) tidal forces. We obtain this value by combining our results from Section V.C. with the probability distribution for encounter velocities between these 24 objects and the Earth. Our calculations show that 34% of Mercury-crossers encounter Earth between 8–12 km/sec, 17% between 12–16 km/sec, 14% between 16–20 km/sec, 4% between 20–24 km/sec, 14% between 24–28 km/sec, 14% between 28–32 km/sec, 2% between 32–36 km/sec, and <1% at velocities >36 km/sec. Using this, and by estimating that 0.5- and 1.0-km binary asteroids approaching Mercury are pulled apart by solar tides if they are separated by 24.5 times the sum of their radii (i.e., one half a Hill radius at 0.387 AU for these components—see Section V.C.), we find that only 8% of the binary asteroids approaching Mercury have their components separated by distances larger than 10 times the sum of their radii (vs 15% for typical Earth-crossing asteroids). By folding these results into the model presented in Section VI.A (modified for Mercury) and by using the doublet formation criteria described in Section VI.B, our results show that 5% of all the craters formed on Mercury are doublets (Fig. 12), smaller than the results found for Earth, Venus, and the Moon, but somewhat larger than those found for Mars.

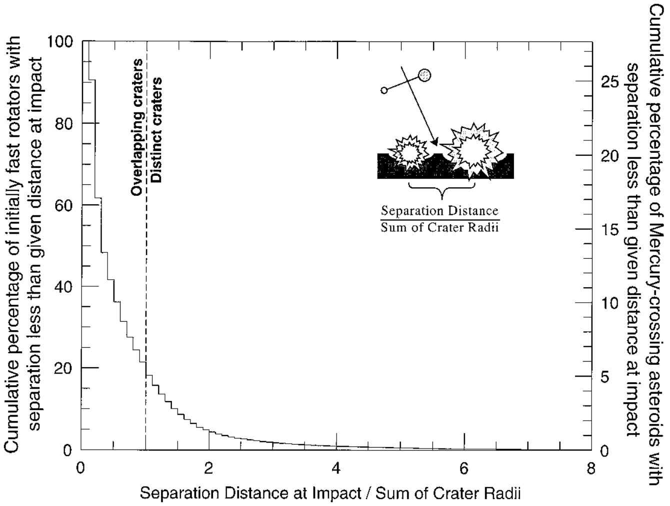

FIG. 12. The fraction of Mercury-crossing asteroids impacting Mercury that produce doublet craters. Axes are labeled the same way as Fig. 9. Only ~5% of these bodies form doublet craters.

VII. DISCUSSION

VII.A. The Search for Asteroid Satellites

Until the discovery of 243 Ida's satellite, Dactyl, by the Galileo spacecraft, asteroid satellites had been an elusive quarry for astronomers. Observers over the years have concentrated their investigations on large main-belt asteroids, which, on average, tend to be brighter and easier to observe than near-Earth asteroids. In this section, we review the history of the search for asteroid satellites.

One of the first indications that asteroid satellites might exist occurred in the 1970's during observations of star occultations by asteroids. Several unexpected star ''blinkouts'' away from the target asteroid suggested that an unseen satellite had moved in front of the star and blocked the star's light from reaching Earth (Van Flandern *et al.* 1979). However, most of these detections were by visual means, making confirmation difficult (Millis and Dunham 1989). At worst, several reported detections may have been spurious (Reitsema 1981). Additional detections using photoelectric occultation techniques were made in the 1980's (Arlot *et al.* 1985) but, by that time, the enthusiasm in the asteroid community for this technique had diminished. In general, occultation observations probably lack the coverage necessary to find satellites much smaller than the primary (Weidenschilling *et al.* 1989).

Several CCD imaging surveys using coronographic techniques to detect asteroid satellites have also been attempted (Gehrels *et al.* 1987, Gradie and Flynn 1988, Stern and Barker 1992). Though 24 main-belt asteroids were investigated, none were shown to have km-sized satellites with large orbits. However, this method would not have found satellites as small or as close as Dactyl was to Ida (C. Chapman, personal communication). It is possible that near-Earth asteroids might provide better targets for this technique (Stern and Barker 1992).

Several lightcurves have been found with shapes consistent with binary asteroids. However, most lightcurves can be fit by a variety of asteroid shapes, making it difficult to find a unique solution (Weidenschilling *et al.* 1989). Moreover, if asteroid satellites are small (i.e., a tenth of the diameter of the primary), any lightcurve features produced would be difficult to distinguish from the primary's lightcurve. Nevertheless, some lightcurves can provide interesting results: Binzel (1985) found that 1220 Crocus had a lightcurve with two distinct periods, diagnostic of an asteroid precessing under the influence of a satellite. Also, Pravec *et al.* (1996) report that near-Earth asteroid 1994 AW_1 has a complex lightcurve which may be consistent with it being a binary. Though more observations are needed to confirm this discovery, 1994 AW_1's low eccentricity (0.076) and semimajor axis (1.1 AU) suggest that it might have encountered the Earth at low enough velocity to have undergone tidal disruption, which in turn could have produced its satellite.

Other, more indirect, evidence for asteroid satellites can be found by examining asteroid rotation periods. Several near-Earth and main-belt asteroids have anomalously long rotation periods and ''tumbling'' rotation motion (e.g., 4179 Toutatis); their origin cannot easily be explained by collisional models (Harris 1994). Chauvineau *et al.* (1995) suggested that a massive satellite may slow down the rotation of its primary before being ejected; their tidal despinning mechanism could account for many asteroids with long rotation periods, though this process probably could not account for Toutatis' very long period (A. Harris, personal communication).

Finally, delay-Doppler radar imaging of near-Earth asteroids such as 4769 Castalia (Ostro *et al.* 1990; Hudson and Ostro 1994) holds great promise for being able to detect asteroid satellites. This technique's success depends largely on the size of the target and its distance from Earth during the observation. Upgrades to the Arecibo telescope, to be completed within the next year or so, may expedite a systematic search for asteroid satellites.

VIII. CONCLUSIONS

We briefly summarize our conclusions from this paper:

- Rubble-pile asteroids, after experiencing a close approach with a planet, frequently undergo tidal fission or tidal stripping of small fragments and form two main components, which, in some cases, begin to orbit one another. Though subsequent close planetary encounters nearly always cause these components to escape one another, other planetary encounters may create new asteroid satellites from the remnant rubble-pile primary.
- Binary asteroids separated by small distances can become well-separated through distant planetary perturbations at encounter and mutual tidal forces acting in the interim between planetary encounters.
- About 15% of all Earth-crossing asteroids should have satellites, and fast-rotating rubble-piles are the most likely objects to undergo tidal fission and produce satellites.
- The steady-state binary asteroid population in the Earth-crossing asteroid region is large enough to produce the fraction of doublet craters found on Earth and Venus (~10%). We predict that the Moon has the same percentage of doublets.
- Rubble-pile asteroids on solely Mars-crossing orbits are unlikely to become well-separated and form doublet craters upon impact with Mars. Our results are consistent with the paucity of doublet craters on Mars (~2 ± 1%) relative to the fraction of doublets found on Earth and Venus.
- Rubble-pile asteroids on Mercury-crossing orbits are dominated by perturbations from Earth and Venus. We predict that only ~5% of all asteroids impacting Mercury produce doublet craters.

We have made a number of predictions in this paper which may be testable with current observational techniques. Moreover, the next slate of near-Earth asteroid spacecraft missions provides an opportunity to image several bodies at much greater resolution that could be hoped for with Earth-based observation techniques. With luck, we may discover a binary asteroid in the near-Earth asteroid population within the next few years, confirming that planetary tidal forces play a strong role in shaping the near-Earth asteroid and the terrestrial crater populations.

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