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NOTE

Can Tidal Disruption of Asteroids Make Crater Chains on the Earth and Moon?

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Crater chains, presumably formed by weak asteroids or comets stretched apart by planetary tides, have been tentatively identified on both the Earth and Moon. By modeling tidal disruption by the Earth and Moon of "rubble-pile" bodies, we find that the Earth disrupts enough objects over the last 3.8 billion years to account for one or two lunar crater chains, but that the reciprocal production rate of terrestrial crater chains is too low to make any in observable geological history. © 1997 Academic Press

A crater chain is a regularly spaced row of three or more impact craters with similar sizes and apparently identical ages. A crater chain is formed when an asteroid or comet with low tensile strength is pulled apart by tides during a close approach to a planet and separates into a train of fragments which then impact a moon of the planet rather than escaping to interplanetary space. The projectiles themselves can only be a few tens of km—or a few seconds—apart at impact. (In this study, we do not consider "secondary" crater chains formed by falling ejecta from a much larger impact, identified by their radial orientation to the source crater, their associations with other secondary features, and their distinctive morphology.) Comet P/Shoemaker-Levy-9 (henceforth "SL9") provided a striking demonstration of tidal disruption during its penultimate encounter with Jupiter in 1992. Chains of craters probably formed by the impacts of fragment trains similar to that of SL9 have been found on Jupiter's Galilean satellites; Voyager images reveal 8 crater chains on Ganymede and 11 on Callisto (Melosh and Schenk 1993; Schenk *et al.* 1996). The chains are all nearly linear, range in length from 60 to 626 km, and consist of between 6 and 25 closely spaced, similarly sized craters.

It has been suggested that two analogous crater chains may exist on Earth's Moon. One potential chain is the relatively fresh (i.e., post-Imbrian) Davy chain, which is 47 km long and contains 23 craters, each 1–3 km in diameter. Although its orientation is roughly radial to Orientale, its morphology and setting imply that it may not be a secondary crater chain (Melosh and Whitaker 1994; Wichman and Wood 1995; Schenk *et al.* 1996). A second is the Abulfeda chain, which is $\gtrsim$3.8 Gyr old, is 200–260 km long, and has 24 craters, each 5–13 km in diameter. Its orientation is not radial to any large impact structure on the Moon (Melosh and Whitaker 1994; Schenk *et al.* 1996).

In addition, recent work has suggested that two crater chains might exist on Earth. One candidate is a string of eight circular depressions (each 3–17 km wide) distributed along a 700 km line spanning Kansas, Missouri, and Illinois. Two of the depressions, Decaturville and Crooked Creek, are known impact craters ~300 Myr old (Rampino and Volk 1996). Another possible terrestrial crater chain includes the 17 km diameter, 360 Myr old Aorounga impact structure in northern Chad and two nearby features recently discovered by radar but not yet verified as craters by field work (Ocampo and Pope 1996). The third structure at Aorounga is indistinct and out of line with the other two; it may be an unassociated crater or not an impact structure at all. If these features do compose a chain, they have a morphology very different from that of the crater chains described above.

The same tidal break-up mechanism that makes crater chains on the Galilean satellites may also make them on the Earth and Moon. To investigate this issue, we model the tidal disruption of km-sized bodies by the Earth and Moon to gauge the rate at which each causes crater chains on the other. The results are compared with the number of observed or postulated crater chains to determine whether they could have formed by this process.

Our model assumes that km-sized Earth-crossing asteroids (ECAs) and comets are "rubble-piles," fragile aggregates of large and small components held together by self-gravity rather than material strength. An increasing body of evidence supports this hypothesis: (a) Studies of the break-up of SL9 suggest that it was weak or without strength (Asphaug and Benz 1996); (b) Observations of asteroid spin rates have yet to reveal an object rotating so quickly that it must be held together by tensile

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strength (Harris 1996); (c) Doublet craters on Earth, Venus, and Mars are probably formed by the impact of binary asteroids, themselves produced by tidal fission in a population dominated by rubble-piles (Bottke and Melosh 1996a, 1996b); (d) Numerical simulations of asteroid impacts suggest that most collisionally evolved asteroids larger than ~1 km are highly fractured (Asphaug and Melosh 1993; Greenberg *et al.* 1994; 1996; Love and Ahrens 1996).

We model the asteroid or comet (henceforth the "progenitor") as an aggregate of 247 identical spherical particles held together by self-gravity. Interparticle collisions are treated rigorously, drawing on experience gained from simulating fractal aggregates and planetary rings (Richardson 1993; 1994; 1995). The tidal disruption code itself is similar to those used in the past by Asphaug and Benz (1996), Solem and Hills (1996), Boss *et al.* (1991), and others. We introduce, however, several modifications which allow us to simulate close encounters between planets and rubble-pile progenitors more realistically.

First, we treat friction explicitly using a coefficient of restitution (ε) of 0.8. We find our results are largely insensitive to the choice of ε as long as collisions are inelastic ($\varepsilon < 1$). The case of $\varepsilon = 1$ is unrealistic and somewhat hampers reaccretion.

Second, we use a nonspherical progenitor with dimensions of $2.8 \times 1.7 \times 1.5$ km ($1.8 \times 1.1 \times 1.0$ normalized), similar to the elongated shape of many near-Earth objects (McFadden *et al.* 1989; Ostro 1993). Our test runs show that spherical progenitors, such as those used by the groups mentioned above, often resist tidal disruption. Use of an elongated progenitor requires that we account for the progenitor's rotational phase (orientation of the long axis) at periapse, θ. When $\theta = 0°$, the long axis or its projection in the orbit plane points directly towards the planet. The effect of θ will be discussed below, and in Richardson, Bottke, and Love (1997, in preparation).

Third, we allow our progenitors to rotate with spin periods P = 4, 6, 8, 10, and 12 hr, similar to those of most ECAs (Harris 1996). Other groups have only used nonrotating progenitors. To include rotation, we must also account for the orientation of the progenitor's rotation pole at periapse. We define this pole orientation using two angles: α, the angle between the rotation pole and the normal of the progenitor's orbit plane; and β, the projected angle between the pole and the vector connecting the progenitor with the center of the Earth or Moon at the instant of closest approach (periapse), measured in the orbit plane. The effect of these angles will be discussed further below and in Richardson, Bottke, and Love (1997, in preparation).

Finally, we test progenitors on hyperbolic encounters with the Earth and Moon, defined using the periapse distance q and pre-encounter velocity "at infinity" v_∞ (i.e., the velocity of a body on a hyperbolic trajectory past the Earth–Moon system before gravitational acceleration becomes significant). Previous models frequently used parabolic encounters which, while providing a useful approximation, did not accurately simulate the trajectories of most comets and asteroids passing near planets.

The progenitor's bulk density is 2 g cm^{-3}, characteristic of porous stone and consistent with the densities of Phobos and Deimos (Thomas *et al.* 1992). Individual particles have density 3.6 g cm^{-3}, similar to that of chondritic meteorites (Wasson 1974). Each simulation begins with the progenitor 15 Roche radii from the planet ($R_{\rm Roche} = 2.46 R_{\rm planet}(\rho_{\rm planet}/\rho_{\rm progenitor})^{1/3}$, where "planet" is the Earth or the Moon), far enough to minimize tidal effects at the outset, but close enough to make exploration of parameter space practical. Each run ends at a post-encounter distance equal to the current separation of the Earth and Moon (~60 Earth radii), where an impact, if any, would occur. A fourth-order polynomial predictor–evaluator–corrector integration engine tracks particle positions and velocities. For precision, the calculation is carried out in the progenitor's center-of-mass frame.

We find several classes of outcomes for these encounters, depending on q, v_∞, P, α, β, θ, and whether the progenitor passes near the Moon or the Earth (Fig. 1). The most severe is "S," an "SL9-type" catastrophic disruption forming a line of clumps of roughly equal size (a "string of pearls") with the largest fragment containing less than 50% of the progenitor's original mass (Fig. 2). In all cases tested, "S" class events produced fragment trains with orientations, sizes, and spacings consistent with the Moon's observed crater chains. Less severe, and incapable of making crater chains, is "B," break-up with mass shedding of clumps (three or more particles) and single particles, with 50% to 90% of the progenitor's mass in the largest fragment. Milder still is "M," mass shedding of clumps or particles, with the progenitor retaining more than 90% of its mass. Finally, "N" class encounters produce no mass loss, but can change the progenitor's shape and rotation state.

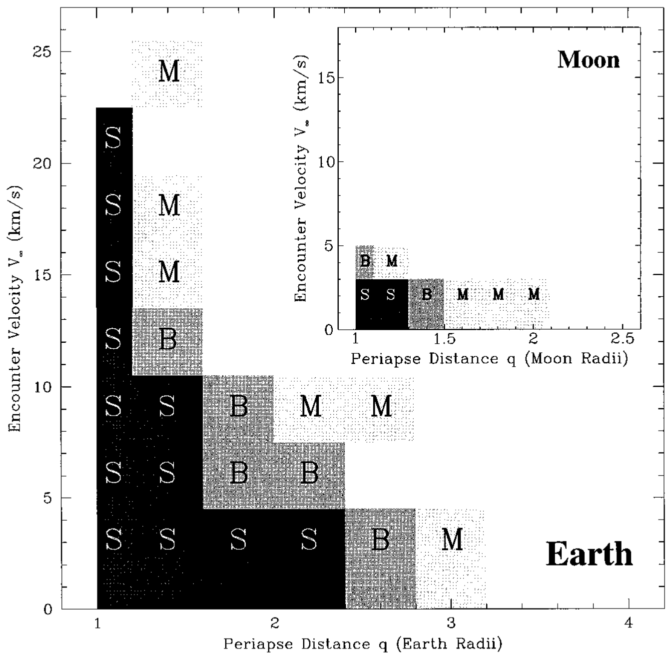
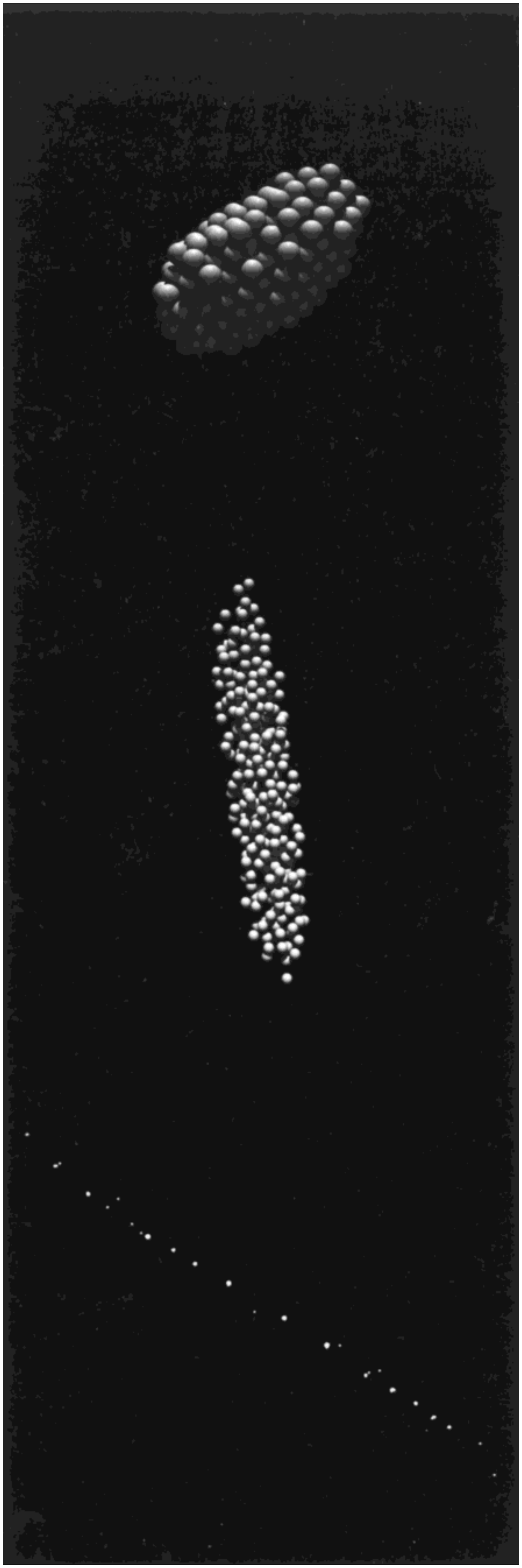


FIG. 1. Tidal disruption outcomes for rubble-pile progenitors with rotation periods of P = 6 hr encountering both the Moon (q = 1.01, 1.2, 1.4, 1.6, 1.8, 2.0, 2.2, 2.4 $R_{\rm MOON}$ and v_∞ = 2, 4, 6, 8, 10, 12, 14, 16 km sec^{-1}) and the Earth (q = 1.01, 1.4, 1.8, 2.2, 2.6, 3.0, 3.4, 3.8 $R_\oplus$ and v_∞ = 3, 6, 9, 12, 15, 18, 21, 24 km sec^{-1}). The outcomes, in decreasing order of severity, are: (S) "Shoemaker-Levy-9-type" catastrophic disruption where the progenitor forms into a line of ~ equal size clumps (i.e., a "string of pearls") and leaves less than 50% of its mass in the largest fragment; (B) Break-up with mass shedding of clumps and single particles, leaving the progenitor with 50%–90% of its original mass; and (M) Mild mass shedding of clumps or particles, leaving the progenitor with over 90% of its original mass. A fourth class, (N), corresponding to possible changes in the progenitor's shape or spin with no mass loss, fills the blank spaces on each plot. The jitter seen in the outcomes is caused by noise in θ as q and v_∞ change. The paucity of S-class events seen near the Moon is partially caused by the gravitational acceleration of the Earth, which substantially increases the periapse velocities of low v_∞ bodies.

Figure 1 shows the results for progenitors with P = 6 hr (the median rotation period of ECAs; Harris 1996) encountering the Earth and Moon over various values of q and v_∞. In the case of the Moon, we find that "S" class events occur only when $q \lesssim 1.2 R_{\rm Moon}$ and $v_\infty \lesssim 2$ km sec^{-1}. "M" and "B" class events occur over a larger range of q and v_∞, but they cannot produce crater chains on Earth. In the case of the Earth, the regime of SL9-type outcomes is much larger, ranging from $q \sim 2 R_\oplus$



at 3 km sec^{-1} to $q \sim 1.2R_{\oplus}$ for 12 km sec^{-1}, near the mean encounter velocity of asteroids with the Earth–Moon system (Bottke *et al.* 1994a, 1994b). We also find that bodies approaching within $q = 1.01R_{\oplus}$ suffer ''S'' class disruptions even if their encounter velocities are as high as 21 km sec^{-1}. Break-up ''B'' and mass shedding ''M'' events also occur more readily near the Earth. The Earth's higher density and larger size explain its greater effectiveness at producing tidal disruptions (Asphaug and Benz 1996).

For both the Earth and the Moon, tidal break-up is more likely at low v_{∞} than at high v_{∞}, presumably because slower progenitors spend more time near periapse. Thus, objects with low (e, i) heliocentric orbits are more susceptible to tidal disruption. This effect may play an important role in the evolution of the ECA population (Bottke *et al.* 1997) and may account for the reported excess of small ECAs found by Spacewatch (Rabinowitz *et al.* 1993; also suggested by Asphaug and Benz 1996; Solem and Hills 1996). In addition, because velocities above 21 km sec^{-1} do not yield SL9-type break-ups, long-period comets (with $\langle v_{\infty} \rangle \sim 55$ km sec^{-1}; Weissman 1982) cannot be tidally disrupted by the Earth or Moon unless their bulk densities are $\ll 1$ g cm^{-3}. For this reason, we do not consider cometary progenitors in the model presented here.

Results for the other spin periods, although not shown here, were similar in character to those at $P = 6$ hours. We note, however, that break-up is enhanced for faster rotators and inhibited for slower rotators.

The progenitor's rotational phase angle θ has a great influence on the outcome of the encounter. For position angles $-90° \lesssim \theta \lesssim 0°$ (leading long axis rotating toward the planet), tidal torque and centrifugal force cooperate to enhance disruption. For $0° \lesssim \theta \lesssim 90°$ (leading long axis rotating away from the planet), tidal torque opposes centrifugal force and breakup is resisted. Our runs show ''S'' class disruptions almost always only occur when $0° < \theta < 90°$. This effect reduces the frequency of SL9-type events by a factor of $\sim$2 from that implied by Fig. 1, assuming that θ is random for ECAs.

The progenitor's rotation pole orientation, defined by α and β, also affects the outcome of each run. Although computational limitations prevented us from testing all values of α and β for each set of q, v_{∞}, and P, we found that the *class* (e.g., S, B, M, or N) of break-up for elongated progenitors is generally insensitive to α and β as long as the rotation is prograde (i.e., $0° \leq \alpha \leq 90°$). More quantitatively, we found that the exact amount of mass lost from the progenitor decreases slightly within each class as α increases. If the rotation is retrograde ($90° \leq \alpha \leq 180°$), however, mass loss is effectively suppressed. If ECAs have random pole orientations, the fraction with retrograde spins (50%) will resist tidal disruption, decreasing the frequency of SL9-type events by another factor of $\sim$2. Thus, an Earth-crossing object has at best a 25% chance of undergoing an SL9-type disruption each time it encounters the Earth or Moon.

We use the results shown in Fig. 1, along with the outcome dependence

FIG. 2. Three snapshots of the tidal breakup by the Earth of a 2 g cm^{-3} asteroid. For this run the asteroid spin period is $P = 6$ hr prograde, the close approach distance is $q = 1.01R_{\oplus}$, and the encounter velocity is $v_{\infty} = 9$ km sec^{-1}. (top) The asteroid before encounter; for scale, each sphere (of the 247 total) is 255 m in diameter and the long axis of the asteroid measures 2.8 km. The spin vector is normal to the orbital plane and points directly out of the page. (middle) The asteroid breaking up shortly (25 min) after perigee (exit from the Roche sphere occurs at 39.5 minutes). At close approach the Earth was directly to the top of this frame. (bottom) The asteroid at the end of the run (i.e., at the instant it crossed the Moon's orbit). Note that 26 distinct fragments (of which 13 are self-gravitating clumps of 3 or more particles, accounting for 94% of the asteroid mass) were created. The largest clump contains 15% of the mass and has a prograde spin period of 7.5 hr. All of the clumps are mutually escaping. The train length at this moment is 162 km.

on rotational phase angle and pole orientation discussed above, as a basis for calculating the mutual crater chain production rate on the Earth and Moon. Such an estimate, however, requires additional information about the impact cross-sections of the Earth and Moon and about the flux, velocities, and spin rates of km-sized Earth-crossing asteroids.

The probability of a body tidally disrupted by the Earth striking the Moon, or vice versa, is found by comparing the gravitational cross-section of the target body with the surface area of a sphere of radius D, where D is the Earth–Moon distance.

We estimated the flux using two components: the size–frequency distribution of km-sized ECAs (Morrison 1992) and the encounter frequency of ECAs with the Earth–Moon system (Bottke *et al.* 1994a, 1994b). For the latter value, we assumed that 197 ECAs (discovered as of April 1996; Minor Planet Center) provide a representative sample of the entire ECA population. The average intrinsic encounter probability of a given ECA with the Earth or Moon was found to be 1.12×10^{-16} km^{-2} yr^{-1}. We adjusted this value for geometrical cross-section and gravitational focusing using the factor $q^2(1 + v_q^2/v_\infty^2)$, where v_q is the escape velocity of the Earth or Moon at a distance q from its center. For ECAs encountering the Earth–Moon system, $\langle v_\infty \rangle = 12.5$ km sec^{-1}. Few ECAs (~5%) have $v_\infty < 5$ km sec^{-1}. The lunar cratering record suggests that this flux of bodies has been constant for the last 3.0 Gyr (Grieve and Shoemaker 1994).

We estimated the velocity distribution of ECAs encountering the Earth–Moon system using the technique of Bottke *et al.* (1994a, 1994b). The ECAs' rotation period distribution was approximated as a Maxwellian with a mean period of 6 hr (A. Harris, personal communication). We truncated this distribution at 3.1 hr, where our progenitors fly apart from centrifugal force. We also neglected the 20% of the ECA population which are extremely slow rotators (i.e., 4179 Toutatis; Hudson and Ostro 1995).

Combining these present-day quantities yields the following results. A km-sized ECA currently has a lifetime against an "S"-class disruption by the Earth of ~450 Myr, compared to a dynamical lifetime of order 10 Myr (P. Farinella *et al.* 1994; Froeschlé *et al.* 1995). Thus, an ECA has about a 2% chance of being catastrophically disrupted by Earth tides before hitting a planet or being ejected from the terrestrial planet region. Because there are ~2100 km-sized ECAs (Morrison 1992), an asteroid should undergo an "S"-class event near the Earth roughly every 210,000 years. This disruption rate, together with the Moon's current distance from the Earth, suggests that a new lunar crater chain is formed about every 35 Gyr. This rate is low enough that we do not expect to find any fresh crater chains on the Moon's near side. The current lifetime of a given ECA against an "S"-class disruption by the Moon is 1100 Gyr. Thus, by again including all 2100 km-sized asteroids, we find that an asteroid should undergo an "S"-class event near the Moon once every 530 Myr. This rate corresponds to a new crater chain on the Earth once every 360 Gyr, far too low to expect any fresh terrestrial crater chains.

Crater chain formation rates are extremely low now, but they were dramatically higher in the past because of the higher ECA flux and smaller Earth–Moon separation distance (i.e., the Moon is known to be gradually receding from the Earth; Burns 1994). The ECA flux in the past can be estimated using the cratering history of the Moon; it suggests that the Moon received as many impacts from 3.8 to ~3.0 Gyr ago as it did during the succeeding 3 Gyr (Hartmann *et al.* 1981). Estimates of the recession rate of the Moon from Earth, however, are many and varied (e.g., Wells 1963; Touma and Wisdom 1994; Sonett *et al.* 1996). We chose to use the "best guess" model of Touma and Wisdom, scaling it to the Moon's formation age of 4.5–4.6 Gyr (J. Touma, personal communication). The adjusted model shows early rapid recession, followed by gradual migration from $49R_\oplus$ to $60.3R_\oplus$ over the last 3.8 Gyr.

Including these effects over the 3.8 Gyr since the Late Heavy Bombardment, we find that there should be ~1 crater chain on the Moon, matching observations of one or two lunar crater chains (Melosh and Whitaker 1996; Schenk *et al.* 1996). The match between model and observation is encouraging, especially given the uncertainties involved. We recognize, however, that small number statistics make the comparison less compelling.

According to our model, the number of crater chains expected on the Earth in the last 3.8 Gyr is less than 0.1. The number expected in 360 Myr is 0.001, inconsistent with resports suggesting that one or two terrestrial crater chains have formed in that time. The inconsistency grows when one considers that a large fraction (~70%) of the Earth is covered by water and that the terrestrial impact record is eroded and biased against small craters.

Because we expect the same population of bodies to encounter both the Earth and Moon, many of the uncertainties in this treatment vanish if we calculate the ratio (rather than absolute numbers) of crater chains on the two bodies. Our findings show that the production rate of crater chains on the Moon is ~10 times the terrestrial rate. Thus, if there are two crater chains on the Earth less than 360 Myr old, we expect about 20 young, fresh crater chains on the Moon's near side. None are seen. We therefore believe that the reported terrestrial crater chains, if real, were not produced by asteroids or comets disrupted by lunar tides.

In this paper, we have so far assumed that crater chains are only produced by the direct impact of an asteroid tidally disrupted by the Earth or Moon. We now examine other possibilities. One scenario calls for a very low v_∞ object to be disrupted during a close Earth encounter before or after capture into Earth orbit by solar or lunar perturbations; the fragment train would then proceed on to impact the Earth or Moon during the next encounter, making a crater chain. A second scenario has an object make an "aerobraking" passage through the Earth's atmosphere, which leads to tidal disruption, capture, and collision during the subsequent pass. A third scenario has the progenitor be tidally disrupted by the Sun or another planet, with the fragment trains proceeding on to impact the Earth or Moon.

These scenarios seem unlikely. The scarcity of very low v_∞ objects aside, capture by the Earth most often occurs when a progenitor is perturbed by the Sun near the edge of Earth's sphere of influence. Throughout subsequent orbital evolution, the progenitor's apogee tends to remain at that distance (e.g., Kary and Dones 1996). For these orbits, the round trip flight time from tidal disruption by the Earth to apogee and back to form a crater chain is about 3 months (Love and Ahrens 1996), ~200 times the flight time for a typical ECA from the Earth to the Moon. Thus, this mechanism would produce crater chains ~200 times longer than observed lunar chains (for example, the projectiles that formed the 47 km Davy chain would have made a 9400 km chain at Earth!), inconsistent with the proposed terrestrial chains. Lunar perturbations are similarly ineffective: a weak perturbation would not shorten the flight time appreciably. A strong one ($\Delta V \sim 1.5$ km/sec) might accelerate the return of the fragment train, but such close encounters with the Moon happen roughly as often as lunar crater chains. This rate is too low to explain the proposed terrestrial crater chains. Aerobraking might disrupt and capture a km-sized body into a low apogee orbit, but on the subsequent pass the fragments would hit the ground at a very shallow angle (if at all), making a distinctive chain with oblique craters. No such chains are observed. We can also rule out tidal disruption by the Sun or by other planets, since the resulting fragment trains would have much more time to spread apart than in the capture scenario discussed above. This conclusion is supported by the lack of crater chains on Mercury, Venus, and Mars, each of which would be a target for chains formed by these other mechanisms (Schenk *et al.* 1996).

In conclusion, if field work verifies that the terrestrial crater chains are real, then our results suggest they are probably secondaries from an unseen (i.e., subducted or eroded away) or unrecognized large terrestrial crater. Lunar crater chains, however, can be explained by our model, suggesting that the tidal disruption of asteroids near Earth is more common than previously thought.

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