THE ASTRONOMICAL JOURNAL, 117:1921–1928, 1999 April

1620 GEOGRAPHOS AND 433 EROS: SHAPED BY PLANETARY TIDES?

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Received 1998 September 9; accepted 1998 November 12

ABSTRACT

Until recently, most asteroids were thought to be solid bodies whose shapes were determined largely by collisions with other asteroids. Recent work by Burns and others has shown that many asteroids may be little more than rubble piles, held together by self-gravity; this means that their shapes may be strongly distorted by tides during close encounters with planets. Here we report on numerical simulations of encounters between an ellipsoid-shaped rubble-pile asteroid and Earth. After an encounter, many of the simulated asteroids develop the same rotation rate and distinctive shape as 1620 Geographos (i.e., highly elongated with a single convex side, tapered ends, and small protuberances swept back against the rotation direction). Since our numerical studies show that these events occur with some frequency, we suggest that Geographos may be a tidally distorted object. In addition, our work shows that 433 Eros, which will be visited by the *NEAR* spacecraft in 1999, is much like Geographos, suggesting that it too may have been molded by tides in the past.
Key words: celestial mechanics, stellar dynamics — minor planets, asteroids

1. INTRODUCTION TO 1620 GEOGRAPHOS

The shapes of several Earth-crossing objects (ECOs) have now been inferred by delay-Doppler radar techniques (Ostro 1993; Ostro et al. 1995; Hudson & Ostro 1994, 1995, 1997). They show that ECOs have irregular shapes, often resembling beat-up potatoes or even contact binaries. It is generally believed that these shapes are by-products of asteroid disruption events in the main belt and/or cratering events occurring after an ECO has been ejected from its immediate precursor. A few of these bodies, however, have such unusual shapes and surface features that we suspect an additional reshaping mechanism has been at work. As we will show, at least one ECO, 1620 Geographos, has the exterior characteristics, orbit, and rotation rate of an object that has been significantly manipulated by planetary tidal forces.

1620 Geographos is an S-type asteroid with a mean diameter slightly over 3 km. It was observed with the Goldstone 2.52 cm (8510 MHz) radar from 1994 August 28 through September 2, when the object was within 0.0333 AU of Earth (Ostro et al. 1995, 1996). A delay-Doppler image of Geographos's pole-on silhouette (Fig. 1) showed it to have more exact dimensions of 5.11 km × 1.85 km (2.76 × 1.0, normalized), making it the most elongated object yet found in the solar system (Ostro et al. 1995, 1996). In addition, Geographos's rotation period ($P = 5.22$ hr) is short enough that loose material near the ends of the body is not strongly bound (Burns 1975). For reference, Geographos would begin to shed mass for $P \lesssim 4$ hr if its bulk density was 2.0 g cm^{-3} (Harris 1996; Richardson, Bottke, & Love 1998).

Geographos's elongated axis ratio was unusual enough to prompt Solem & Hills (1996) to advance the hypothesis that it may not have resulted from collisions. Instead, they speculated that it could be a by-product of planetary tidal forces, which kneaded the body into a new configuration during an encounter with Earth.

To test their hypothesis, they employed a numerical N-body code to track the evolution of nonrotating strengthless spherical aggregates making close slow passes by Earth. Some of their test cases showed that tidal forces stretch spherical progenitors into cigar-like figures as long or longer than the actual dimensions of Geographos. Since ECOs undergo close encounters with Earth (and Venus) with some frequency (Bottke et al. 1994), Solem & Hills (1996) postulated that other ECOs may have comparable elongations.

Though Geographos's elongation is provocative, it is, by itself, an inadequate means of determining whether the asteroid has been modified by tidal forces. To make a truly compelling case that 1620 Geographos is a tidally distorted object, the following key issues must be addressed.

Issue A.—Is Geographos's internal structure (or that of any other ECO) weak enough to allow tidal forces to pull it apart?

Issue B.—How likely is it that Geographos ever made a close slow encounter with a large terrestrial planet such as Earth or Venus?

Issue C.—Can tidal forces reshape an ECO into a Geographos-like silhouette (not just an asymmetric elongated figure) and reproduce its spin rate?

Issue D.—If so, how often do such events occur?

Issue E.—Is Geographos a singular case, or have other ECOs undergone comparable distortion?

In the following sections, we will address each of these

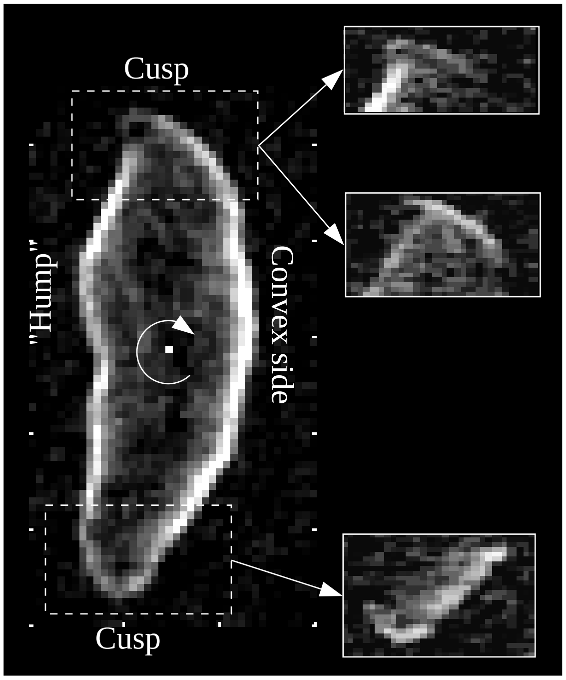

FIG. 1.—1620 Geographos's pole-on shape determined from delay-Doppler observations taken in the asteroid's equatorial plane (Ostro et al. 1996). This image has been constructed from multirun sums of 12 coregistered images, each 30° wide in rotation phase space. The central white pixel indicates the body's center of mass. Rotation direction is indicated by the circular arrow. Brightness indicates the strength of radar return, arbitrarily scaled. Despite substantial smearing of the periphery features, some distinguishing characteristics can be observed: (1) The long axis is tapered on both ends, with one tip narrow and the other more pinched and squat. (2) One side is smooth and convex; the opposite side has a "hump". (3) Cusps at each end are swept back against the rotation direction, giving the body the appearance of a pinwheel when viewed from various aspect angles. The insets show close-ups from three of the 12 summed coregistered 30° images used to make the composite image; they have resolution of 500 ns × 1.64 Hz (75 × 87 m). The cusps are more prominent here, although considerable smearing remains.

questions in turn. Our primary investigative tool for these issues is the *N*-body code developed by Richardson et al. (1998), which is more advanced than the code by Solem & Hills (1996) and is capable of determining the ultimate shape and rotation of the progenitor bodies. By applying a reasonable set of ECO starting conditions, we will show that Geographos-type shapes and spins are a natural consequence of tidal disruption. The results discussed here are based on the extensive parameter-space surveys completed for Richardson et al. (1998).

2. ISSUE A: EVIDENCE THAT ECOS ARE "RUBBLE PILES"

Planetary tidal forces are generally too weak to modify the shapes of solid asteroids or comets, unless the bodies are composed of very weak material (Jeffreys 1947; Öpik 1950). Recent evidence, however, supports the view that most kilometer-sized asteroids (and comets) are weak "rubble piles," i.e., aggregates of smaller fragments held together by self-gravity rather than material strength (Burns 1999; Chapman 1978; Love & Ahrens 1996). Here we list a few salient points, referring the reader to Richardson et al. (1998) for additional information.

1. Comet Shoemaker-Levy 9 (SL 9) underwent tidal disruption when it passed within 1.6 planetary radii of Jupiter in 1992; numerical modeling suggests that this could only have happened if SL 9 were virtually strengthless (Asphaug & Benz 1996).
2. C-class asteroid 253 Mathilde has such a low density (1.3 g cm^{-3}; Veverka et al. 1998; Yeomans et al. 1998) compared with the inferred composition of its surface material (i.e., if carbonaceous chondrite–like, it would have a density of about 2 g cm^{-3}; Wasson 1985) that its interior must contain large void spaces, small fragments with substantial interparticle porosity, or a combination of the two.
3. A set of 107 near-Earth and main-belt asteroids smaller than 10 km shows no object with a rotation period shorter than 2.27 hr; this spin rate matches the value at which centrifugal forces would begin to cause rubble-pile bodies to fly apart (Harris 1996).
4. According to numerical simulations of asteroid impacts, most collisionally evolved bodies larger than about 1 km are highly fractured (Asphaug & Melosh 1993; Greenberg et al. 1996; Love & Ahrens 1996).
5. All of the small asteroids (or asteroid-like bodies) imaged so far by spacecraft (e.g., 253 Mathilde, 243 Ida, 951 Gaspra, and Phobos) have large craters on their surface, implying that their internal structures are sufficiently broken up to damp the propagation of shock waves, thus limiting the effects of an impact to a localized region (Asphaug 1998). If this were not the case, many of these impacts would instead cause a catastrophic disruption.

If these lines of evidence have been properly interpreted, we can conclude that Geographos (and other ECOs) are probably rubble piles, since ECOs are generally thought to be collisionally evolved fragments derived from catastrophic collisions in the main belt. Thus, we predict that Geographos is weak enough to be susceptible to tidal distortion during a close pass with a planet.

3. ISSUE B: PROBABLE ORBITAL EVOLUTION OF 1620 GEOGRAPHOS

If Geographos is a tidally distorted object, it had to encounter a planet at some time in the past. Not just any encounter will do, however. Tidal forces drop off as the inverse cube of the distance between the bodies, such that distant encounters far outside the planet's Roche limit cause negligible damage to the rubble pile. High-velocity trajectories past a planet leave little time for tidal forces to modify the rubble pile's shape. Thus, we need to estimate the probability that Geographos has made a close slow encounter with Earth or Venus.

The orbits of ECOs evolve chaotically. Many of them have orbits that allow them to encounter multiple planets, and the terrestrial planet region is crisscrossed with secular and mean motion resonances (Froeschlé et al. 1995; Michel & Froeschlé 1997; Michel 1997). For these reasons, it is impossible, with any accuracy, to track the orbital motion of any ECO more than a few hundred years into the past or future. The only way, therefore, to assess the likelihood that Geographos had a planetary encounter in the past is to numerically integrate its orbit with that of many clones, in the hope that broad evolution patterns can be readily characterized. To this end, following the procedure of Michel, Froeschlé, & Farinella (1996), we used a Bulirsch-Stoer variable step size integration code, optimized for dealing accurately with close encounters, to track the evolution of eight Geographos-like test clones. We integrated the nominal orbit with $a = 1.246$ AU, $e = 0.335$, and $i = 13.^\circ34$; the other clones were defined by slightly changing their orbital parameters one at a time. All of the planets were included except Pluto. Orbital parameters were provided by the JPL's Horizons on-line ephemeris system, version 2.60.[1] Each clone was followed for 4 Myr.

In general, we determined the orbital evolution of the clones to be controlled by two mechanisms: close encounters with Earth and overlapping secular resonances ν_{13} and ν_{14} involving the mean precession frequencies of the nodal longitudes of the Earth and Mars orbits (Michel & Froeschlé 1997; Michel 1997). We found that five of the eight clones (62.5%) had their inclinations increased by these resonances. This trend raises the possibility that these mechanisms could have affected Geographos's orbit in the past and consequently that its inclination has been pumped up from a lower value. Similarly, six of the eight clones (75%) had their orbital eccentricities increased by the ν_2 and ν_5 secular resonances with Venus and Jupiter. Lower eccentricities and inclinations in the past imply that close approaches to Earth were even more likely to occur and to happen at the low velocities conducive for tidal disruption, in agreement with integrations by other groups (e.g., Froeschlé et al. 1995). Thus, these integrations moderately increase our confidence that Geographos has been stretched by tides in the past.

4. ISSUE C: TIDAL DISRUPTION MODEL AND RESULTS

4.1. *The Model*

To investigate the effects of planetary tides on ECOs (cf. Solem & Hills 1996), we have used a sophisticated N-body code to model Earth flybys of spherical-particle aggregates (Bottke, Richardson, & Love 1997, 1998; Richardson et al. 1998). Our goal in this section is to determine whether Geographos-like shapes are common by-products of tidal disruption. Model details, analysis techniques, and general results are described in Richardson et al. (1998). For brevity, we review only the basics here.

The particles' motions are tracked during the encounter using a fourth-order integration scheme that features individual particle time steps (Aarseth 1985). This method allows us to treat interparticle collisions rigorously, including a coefficient of restitution to produce energy loss (i.e., friction), whereas previous models usually assumed elastic or perfectly inelastic collisions. Note that if energy dissipation is not included, clumps formed by gravitational instability are noticeably less tightly bound (Asphaug & Benz 1996).

The code is capable of modeling tidal disruption over a range of rubble-pile shapes, spin rates, spin axis orientations, and hyperbolic trajectories. To verify that the code was accurate enough to model shape changes realistically, we consulted two experts in granular media, J. Jenkins of Cornell University and C. Thornton of Aston University in the UK. Based on their suggestions, we checked our code against some standard diagnostic tests in the field. For our first test, we numerically modeled spherical particles being dropped into a pile along a flat surface. Our results showed that we were able to reproduce an empirically derived angle of repose. For a second test, we examined the pre– and post–planetary encounter particle configurations of our rubble piles to determine whether their shapes were artifacts of a crystalline lattice structure (i.e., "cannonball stacking"). Our results showed that lattice effects are nearly unavoidable in rubble-pile interiors, especially when same-sized spherical particles are used, but that the outer surfaces of our rubble piles had essentially randomized particle distributions. Thus, based on our success with these tests and the positive comments of the granular-media experts, we have some confidence that our N-body code yields reasonable results.

Our model rubble piles had dimensions of $2.8 \times 1.7 \times 1.5$ km, our choice for a representative ECO shape (Richardson et al. 1998), and they had bulk densities of 2 g cm^{-3}, similar to the estimated densities for Phobos and Deimos (Thomas et al. 1992). Note that this value may be overly conservative, given the 1.3 g cm^{-3} density found for Mathilde. Individual particles have densities of 3.6 g cm^{-3}, similar to ordinary chondritic meteorites (Wasson 1995). For most test cases, our rubble pile consisted of 247 particles, with each particle having a diameter of 255 m. Same-sized particles were chosen for simplicity; future work will investigate more plausible particle size distributions. Cases deemed interesting were examined further using rubble piles with 491 same-sized particles. In these instances, particle densities were modified to keep the aggregate's bulk density the same as before. We found that the change in resolution did not significantly modify the degree of mass shedding, the final shape, or the final spin rate of the model asteroid, although it did make some shape features more distinctive.

The tidal effects experienced during a rubble pile's close approach to Earth are determined by the rubble pile's trajectory, rotation, and physical properties. To investigate such a large parameter space, Richardson et al. (1998) systematically mapped their outcomes according to the asteroid's perigee distance q (between 1.01 and 5.0 Earth radii), approach speed v_∞ (between 1.0 and 32 km s^{-1}), rotation period P (tested at $P = 4$, 6, 8, 10, and 12 hr for prograde rotation, $P = 6$ and 12 hr for retrograde rotation, and the no-spin case $P = \infty$), spin axis orientation (obliquity varied between 0° and 180° in steps of 30°), and orientation of the asteroid's long axis at perigee (tested over many angles between 0° and 360°). We discuss the outcomes below, especially those pertaining to Geographos.

4.2. *Tidal Disruption Outcomes*

Several distinct outcomes for tidal disruption were found by Richardson et al. (1998). The most severely disrupted rubble piles were classified as "S," an "SL 9–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. Less severe disruptions were classified as "B", signifying breakup events where 10% to 50% of the rubble pile was shed into clumps (three or more particles) and single particles. Mild disruption events were classified as "M," with the progenitor losing less than 10% of its mass. As we will show below, each outcome class is capable of producing Geographos-like elongations and spin rates.

4.3. *Reshaping Rubble Piles with Planetary Tidal Forces*

To quantify shape changes, we measured the length of each of the rubble pile's axes after an encounter ($a_1 \geq a_2 \geq$

[1] http://ssd.jpl.nasa.gov/horizons.html

a_3), calculated the axis ratios ($q_2 \equiv a_2/a_1$ and $q_3 \equiv a_3/a_1$), and defined a single-value measure of the remnant's "ellipticity" [$\epsilon_{rem} \equiv 1 - \frac{1}{2}(q_2 + q_3)$]. For reference, our progenitor has $\epsilon_{rem} = 0.43$ and the value for Geographos is $\epsilon_{rem} = 0.64$.

Sampling a broad set of parameters to map tidal disruption outcomes, Richardson et al. (1998) identified 195 S-, B-, and M-class events produced with an $\epsilon_{rem} = 0.43$ rubble pile. Figure 2 shows this set with ellipticity plotted against the fraction of mass shed by the progenitor during tidal disruption.

We find that, in general, S-class events tend to yield lower ellipticity values; only two of the 79 outcomes are likely to have a Geographos-like elongation ($\epsilon_{rem} > 0.60$). The mean value of ϵ_{rem} for the S-class events is 0.22 with standard deviation $\sigma = 0.14$. The near-spherical shapes produced by S-class events are a by-product of gravitational instabilities in the fragment chain, which readily agglomerate scattered particles as they recede from the planet.

B-class events do not show a simple trend with respect to ellipticity, though these values tend to increase as the degree of mass shedding decreases. We find that 5 of 40 outcomes have Geographos-like ϵ_{rem} values. The mean value of ϵ_{rem} for all 40 B-class events is 0.45 ($\sigma = 0.14$), very close to the starting ellipticity of 0.43.

M-class events are most effective at increasing ϵ_{rem} and creating Geographos-like shapes, probably because tidal torques must first stretch and/or spin up the rubble pile before particles or clumps can be ejected near the ends of the body. Figure 2 shows 23 of 76 M-class events with Geographos-like ϵ_{rem} values. Overall, the 76 outcomes have a mean $\epsilon_{rem} = 0.54$ with $\sigma = 0.10$. Thus, getting a Geographos-like ellipticity from an M-class disruption is less than a 1 σ event, decent odds if such disruptions (and $\epsilon_{rem} = 0.43$ progenitors) are common.

4.4. *Spin-Up and Spin-Down with Planetary Tidal Forces*

Tidal disruption also changes the spin rates of rubble piles. This can be done by applying a torque to the nonspherical mass distribution of the object, redistributing the object's mass (and thereby altering its moment of inertia), removing mass (and angular momentum) from the system, or some combination of the three. Figure 3 shows the spin periods of the remnant rubble piles (P_{rem}) for the 195 disruption cases described above. Recall that the range of starting P values was 4, 6, 8, 10, and 12 hr for prograde rotation, $P = 6$ and 12 hr for retrograde rotation, and the no-spin case $P = \infty$.

The mean spin period for 79 S-class outcomes is 5.6 ± 2.2 hr, while the comparable value for the 40 B-class and 76 M-class events is 5.2 ± 1.1 and 4.9 ± 1.1 hr, respectively. Note that these last two values are close to the real spin period of Geographos (5.22 hr). These similar values indicate that mass shedding only occurs when the kilometer-sized bodies are stretched and spun up to rotational breakup values. The final rotation rate of the rubble pile is then determined by the extent of the mass loss; in general, more mass shedding (S-class events) means a loss of more rotational angular momentum, which in turn translates into a slower final spin rate. Though the points of Figure 3 do show some scatter, the 195 disruption events together have a mean P_{rem} value of 5.2 ± 1.7 hr, once again a good match with Geographos.

4.5. *Matching the Shape and Spin of 1620 Geographos*

Now that we have found tidal disruption outcomes matching Geographos's ellipticity and spin rate, we can

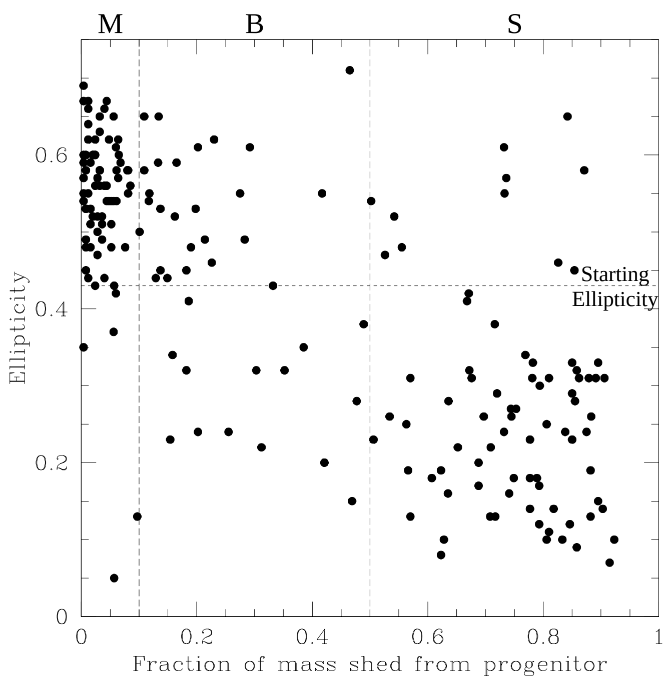

FIG. 2.—Ellipticity values of our model asteroids plotted against the fraction of mass shed in each tidal disruption outcome. Seventy-nine S-class, 40 B-class, and 76 M-class disruptions are shown. The starting ellipticity for our model rubble pile is $\epsilon_{rem} = 0.43$. Geographos's ellipticity is $\epsilon_{rem} = 0.64$. Note that most M-class disruptions produce high ellipticities.

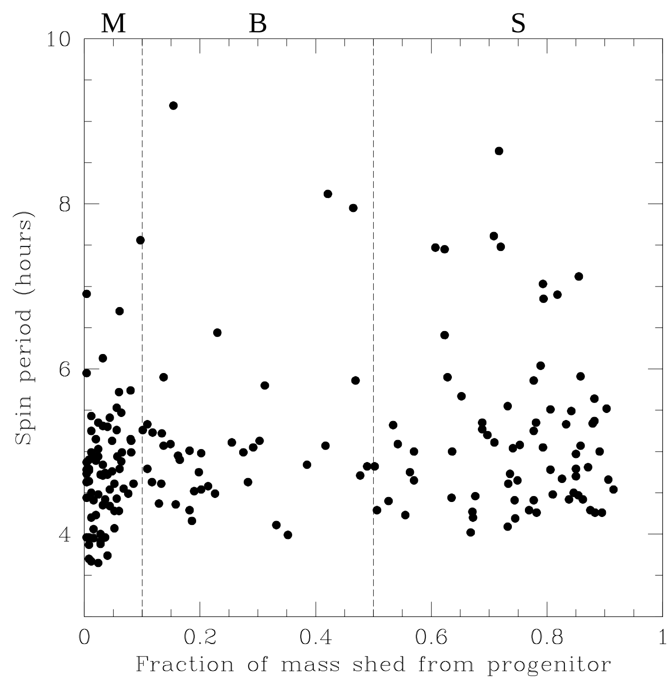

FIG. 3.—Final spin periods of our model asteroids plotted against the fraction of mass shed in each of the 195 S-, B-, and M-class outcomes. Starting spin periods are $P = 4$–12 hr and $P = \infty$ (i.e., no spin). Note that three S-class and one M-class events have final spin periods between 10 and 20 hr (i.e., beyond our $P = 10$ hr plotting limit). Regardless of the starting spin period, most disruptions spin up the model asteroid to $P < 6$ hr.

take a closer look at the resultant shapes of the rubble piles themselves. Our goal is to find distinctive features that match comparable features on Geographos and are possibly antithetical to a collisional origin. To make sure we can resolve these features, we have used a rubble pile containing nearly twice the number of components as before (491 particles). Figure 4 shows this body going through a M-class event with the following encounter parameters: $P = 6$ hr prograde, $q = 2.1$ Earth radii, and $v_\infty = 8$ km s^{-1}.

Figure 4*a* shows the asteroid before an encounter. The spin vector is normal to the orbital plane and points directly out of the page. The asteroid's equipotential surface (to which a liquid would conform) is a function of local gravitational, tidal, and centrifugal forces. At this stage, it hugs the outer surface of the rubble pile.

Figure 4*b* shows the body shortly after perigee passage. Here, the equipotential surface becomes a more elongated ellipsoid with its longest axis oriented toward Earth. Differential tidal forces, greatest at perigee, and centrifugal effects combine to set the particles into relative motion, producing a landslide toward the ends of the body. Particles above the new angle of repose roll or slide downslope to fill the "low spots" and, thereby, further modify the body's potential. As a consequence, the rubble pile is elongated and, as the planet pulls on the body, its rotation rate altered. The action of Earth stretches the model asteroid and, by then

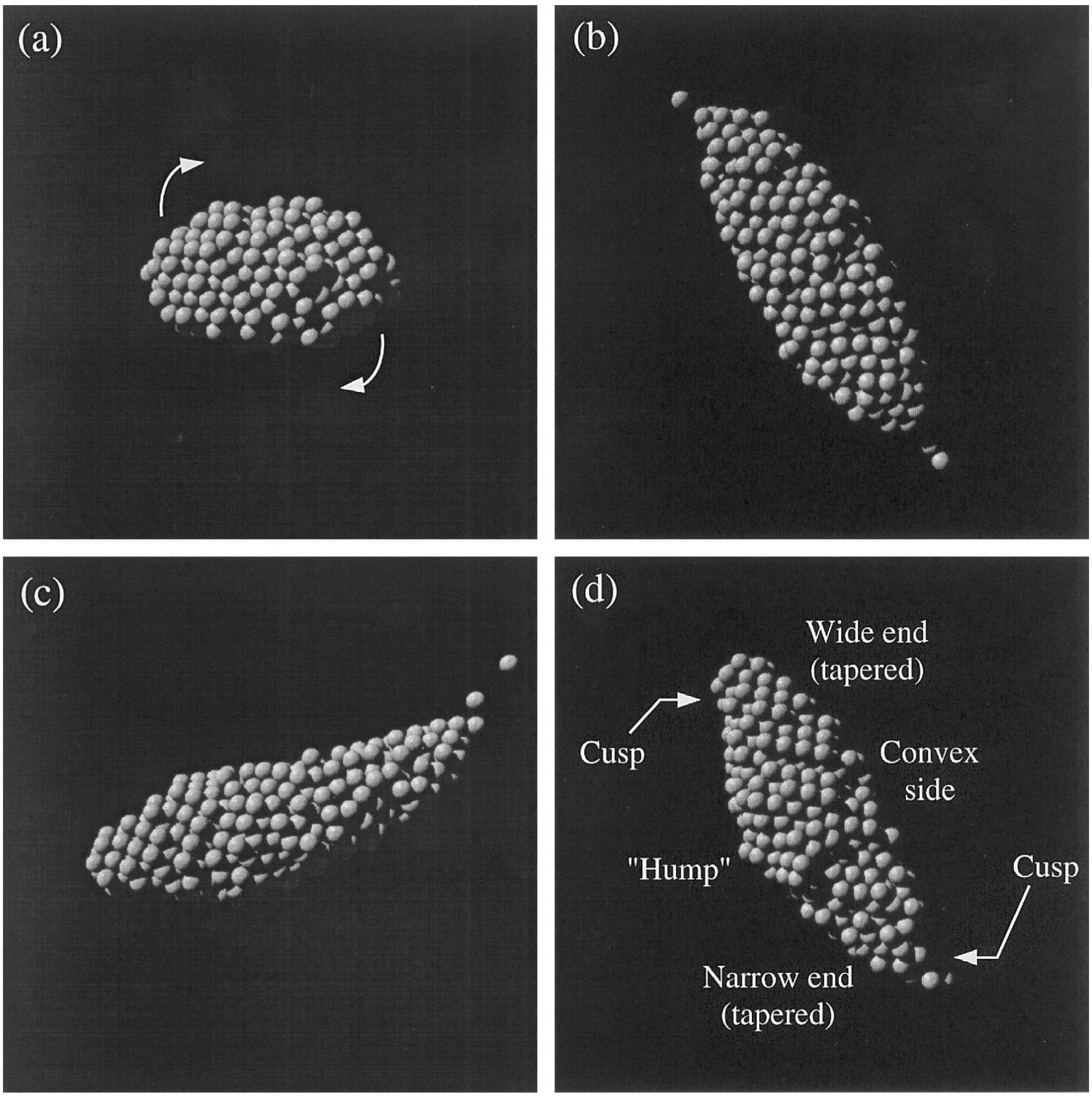

FIG. 4.—Four snapshots of the tidal breakup by Earth of a $P = 6$ hr prograde rotating rubble pile having $q = 2.1$ Earth radii, and $v_\infty = 8$ km s^{-1}. (*a*) The asteroid before encounter. (*b*) The body shortly after perigee passage. (*c*) The later stages of tidal disruption as the body recedes from Earth. Particles shed near the tips do not return to the rubble pile. (*d*) The final shape of the object. Its spin ($P = 5.03$ hr) and elongation (about 2.9 times the mean diameter of the minor axes, or $\epsilon_{\rm rem} \sim 0.65$) are virtually identical to those of Geographos (Fig. 1). Spiral distortion associated with tides produces a smooth convex surface along the long axis, cusps on either end, and a "humplike" mound of material on the opposing side.

pulling on the distorted mass, spins it up, increasing its total angular momentum. Mass ejection occurs when the total force on a particle near the asteroid's tips is insufficient to provide the centrifugal acceleration needed to maintain rigid-body rotation.

Figure 4*c* shows the later stages of the landslide. Particles near the tips are swept backward in the equatorial plane by the asteroid's rotation. The material left behind frequently preserves this spiral signature in the form of cusps pointing away from the rotation direction. Note that these cusps are easy to create but difficult to retain with identical spherical particles at this resolution; we believe that real rubble piles, with rough or craggy components, would more readily "freeze" in position near the ends. Particle movement along the long axis is not uniform; shape changes, increased angular momentum, and mass shedding cause one side of the body to become bowlike. This effect produces a convex surface along the long axis and a "humplike" mound of material on the opposite side.

Figure 4*d* shows the final shape of the object. The spin ($P_{\rm rem} = 5.03$ hr) and ellipticity ($\epsilon_{\rm rem} = 0.65$) are virtually identical to those of Geographos (Fig. 1). The shapes of the two ends are, surprisingly, not symmetric. We believe this is caused by the starting topography, which can play a decisive role in the effectiveness of tidal deformation. The strength of tidal and centrifugal terms depends on each particle's position (Hamilton & Burns 1996), such that some particles lie farther above the local angle of repose than others. Since our model asteroid, like real ECOs, is neither a perfect ellipsoid nor a readily adaptable viscous fluid, the new distorted shape is influenced by the body's granular nature (i.e., friction and component size affect the strength of the landslide). Hence, particles leak more readily off one end than the other, a process that is often accentuated by limited particle movement before the rubble pile reaches perigee. The end that sheds more mass frequently becomes elongated, tapered, and narrow when compared with the stubbier antipode. The overall final shape of the body is much like that of a porpoise or "Shmoo." A comparison between Figure 1 and Figure 4 shows a good match; all of Geographos's main features have been reproduced.

5. ISSUE D: PRODUCTION RATE OF GEOGRAPHOS-SHAPED OBJECTS

As described above, certain S-, B- and M-class disruptions can leave rubble piles with highly elongated shapes and fast spin rates. To estimate the frequency of those particular disruption events near Earth and Venus, we use the technique developed by Bottke et al. (1998), combining a "map" of tidal ellipticity results (described by Richardson et al. 1998) with probability distributions based on ECO spins, ECO spin axis orientations, ECO close approaches with Earth and Venus, and ECO encounter velocities with Earth and Venus. Our results show that a typical ECO should undergo an S-, B-, or M-class event once every $\sim$65 Myr, comparable to an ECO's collision rate with Earth and Venus (Richardson et al. 1998). Similarly, this same body should assume a Geographos-like ellipticity ($\epsilon_{\rm rem} > 0.60$) once every $\sim$560 Myr. The most likely disruption candidates have low *e*'s and *i*'s, consistent with Geographos's probable orbital history (see § 3). Since the dynamical lifetime of ECOs against planetary collision, comminution, or ejection by Jupiter is thought to be on the order of 10 Myr (Gladman et al. 1997), we predict that approximately 15% of all ECOs undergo S-, B- or M-class disruptions (i.e., 10 Myr/65 Myr), and that about 2% of all ECOs (10 Myr/560 Myr) should have shapes (and spins) like Geographos's. The implications of this prediction are discussed below.

6. ISSUE E: OTHER GEOGRAPHOS-LIKE OBJECTS

6.1. *Detecting Tidally Distorted ECOs*

Our estimate that 2% of all rubble-pile ECOs should have Geographos-type shapes and spin periods is, at best, only accurate to a factor of several, given the many unknown quantities we are modeling and the relatively unknown shape distribution of the ECO population. Still, the following thought experiment is useful in providing a crude "reality check." 1620 Geographos has a mean diameter of 3 km and an absolute magnitude of $H = 15.6$ (from Horizons). Morrison (1992) estimates that there are roughly 100 ECOs with absolute magnitudes brighter than 15.0 (6 and 3 km diameters, respectively, for the dark C's and bright S's). Since 2% of 100 objects is two objects, it is perhaps not surprising that we have not noticed more Geographos-like asteroids.

Alternatively, one could argue that, given these odds, it was fortunate to have discovered Geographos's shape in the first place, especially considering that only 35% of the $H < 15.0$ ECOs have been discovered and that relatively few of them have had their shapes determined by delay-Doppler radar (Morrison 1992). It is useful to recall, however, that the known ECO population is biased toward objects that pass near Earth on low-inclination orbits (Jedicke 1996), exactly the class of objects favored to undergo tidal disruption. Hence, the discovery of Geographos's shape among a limited sample of ECOs may not be a fluke, and we predict that more Geographos-like objects are lurking in the undiscovered ECO population.

Our investigation of Geographos led us to examine a second asteroid, 433 Eros, which shares many of Geographos's distinguishing characteristics. We believe Eros may also be tidally distorted, as we will discuss further below.

6.2. *Application to 433 Eros*

Our success in suggesting an explanation for Geographos has led us to consider the next most elongated example, S-class asteroid 433 Eros, the target of the *NEAR* mission. Eros has many of the same distinguishing characteristics as Geographos (and our B- and M-class remnant rubble piles). Visual and radar observations taken during a 0.15 AU pass near Earth in 1975 report that Eros has a short rotation period (5.27 hr) and a highly elongated shape (36 × 15 × 13 km; 2.77 × 1.2 × 1.0, normalized; ellipticity $\epsilon_{\rm rem} = 0.61$) (Zellner 1976; McFadden, Tholen, & Veeder 1989; Mitchell et al. 1998). Both values are comparable to those recorded for Geographos and for 15% (30 out of 195) of our S-, B-, and M-class disruption cases. We caution, however, that these values are not always diagnostic; main-belt asteroid 243 Ida is also elongated (53 × 23 × 18 km) and has a fast spin rate ($P = 4.6$ hr), yet it is definitely not tidally distorted.

Even more intriguing, however, is Eros's pole-on silhouette, which, after modeling the older Goldstone radar data, looks something like a kidney bean (Fig. 5) (Mitchell et al. 1998). One must be careful not to overinterpret this shape, since it is based on data that have a signal-to-noise ratio of approximately 70, while the shape has been "fitted" to a reference ellipsoid that can eliminate discriminating fea-

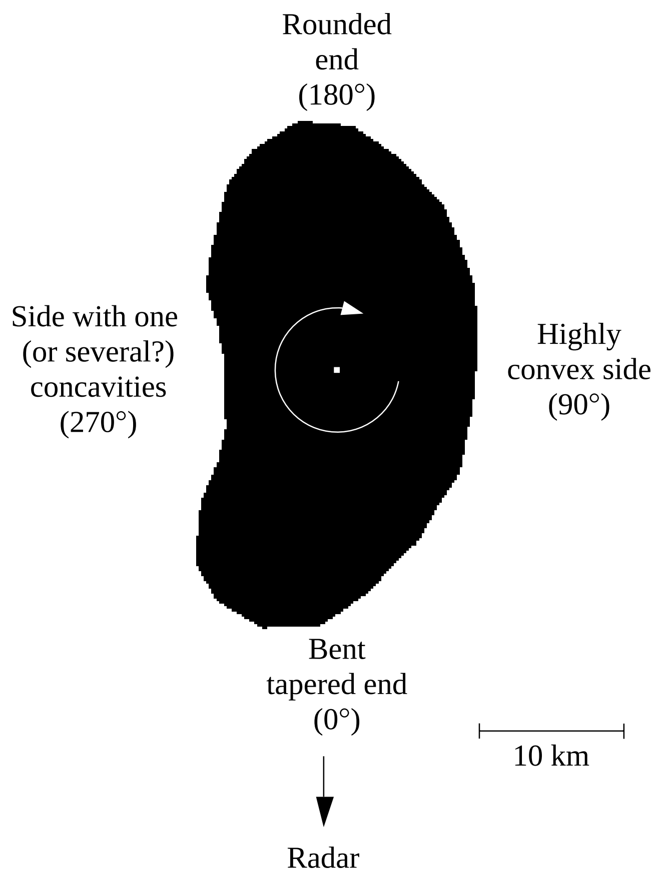

FIG. 5.—Pole-on silhouette of Eros, based on a model in which radar data were fitted to a reference ellipsoid using 508 triangular facets defined by 256 vertices (Mitchell et al. 1998). The silhouette is viewed from the asteroid's south pole. Center of figure, center of rotation, and rotation direction are defined as in Fig. 1. The body is tapered along its length, with a smooth convex side on the right and one or more concavities on the left, making it look something like a kidney bean. Resolution does not permit interpretation of the concavities on the left side (i.e., whether they are craters, troughs, or bends in Eros's shape).

tures. In fact, the concave side of the kidney-bean shape may not be a single concavity, but several adjacent ones. Still, we believe it plausible that Eros's arched back and tapered ends are analogs of similar features on Geographos that were produced by spiral deformations associated with tidal forces. Images from the *NEAR* spacecraft should readily resolve this issue.

NEAR will offer several additional ways to test our hypothesis. Regardless of whether Eros is covered by regolith or bare rock, spectroscopic measurements will suggest a surface composition that can be directly compared with terrestrial rock samples. If the densities of these samples are substantially larger than Eros's bulk density, we can infer that Eros is probably a rubble pile. While observations of large craters would support the rubble pile scenario, too many would weigh against the tidal disruption scenario; global landslides caused by a relatively recent tidal disruption event should modify or bury craters. For this reason, we expect most tidally distorted objects to have relatively young and spectroscopically uniform surfaces. However, the unknown dynamical history of Eros makes any prediction problematic. Landslides also sort debris as it goes downhill; high-resolution images near the ends of Eros may not only show cusplike features but a prevalence of small fragments. An estimate of the spatial distribution of block sizes inside Eros may come from *NEAR*'s gravity field maps. Finally, the results of Bottke & Melosh (1996a, 1996b) and Richardson et al. (1998) show that asteroids affected by tides may often have small satellite companions that were torn from the original body. Thus, the presence of a small moon about Eros would be a strong indication that it had undergone tidal fission.

A possible problem, dynamically speaking, is that Eros is currently an Amor asteroid on a solely Mars-crossing orbit ($a = 1.46$ AU, $e = 0.22$, $i = 10\overset{\circ}{.}8$). Test results show that tidal disruption events occur relatively infrequently near Mars, since it is a weak perturber (Bottke & Melosh 1996a). Studies of Eros's orbital evolution, however, suggest that it may have been on a low-inclination, deeply Earth-crossing orbit in the past (Michel, Farinella, & Froeschlé 1998). Numerical integrations of Eros-type clones show that secular resonances ν_4 and ν_{16} probably modified Eros's orbital parameters, decreasing its eccentricity enough to place it out of reach of Earth, while increasing Eros's inclination to its current value (Michel et al. 1996; Michel 1997; Michel et al. 1998). If true, Eros would have been prone to low-velocity Earth encounters (and tidal disruption) in some past epoch.

7. CONCLUSIONS

Current evidence implies that kilometer-sized asteroids and comets are rubble piles. When these objects, in the form of ECOs, encounter a planet such as Earth, S-, B-, and M-class tidal disruptions frequently produce elongated objects ($\epsilon_{\rm rem} > 0.6$) with fast spin rates ($P \sim 5$ hr). These values are consistent with at least two objects in near-Earth space, 1620 Geographos and 433 Eros, that may have undergone a close slow encounter with Earth or Venus in the past. In addition, the shapes of our model asteroids that have been heavily distorted (and disrupted) by Earth's or Venus's tidal forces resemble the radar-derived shapes of Geographos (and possibly Eros). Estimates of the frequency of tidal disruption events indicate that a small but detectable fraction of the ECO population should have Geographos-like spins and shapes. For these reasons, we believe that planetary tidal forces should be added to collisional processes as a recognized and important geological process that is capable of modifying small bodies.

We thank L. Benner, J. A. Burns, P. Farinella, S. Hudson, J. Jenkins, S. Ostro, and C. Thornton for useful discussions and critiques of this work. We also thank E. Asphaug and C. Chapman for their constructive reviews of the manuscript. P. M. worked on this paper while holding an External Fellowship from the European Space Agency. D. C. R. was supported by grants from the NASA Innovative Research Program and the NASA High-Performance Computing and Communications Program Earth and Space Sciences Project. Preparation of the paper was partly supported by NASA grant NAGW-310 to J. A. Burns.

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