1620 Geographos and 433 Eros: Shaped by Planetary Tides?

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Received 23 September 1998; accepted 10 December 1998
ABSTRACT

Until recently, most asteroids were thought to be solid bodies whose shapes were determined largely by collisions with other asteroids (Davis et al., 1989). It now seems that many asteroids are little more than rubble piles, held together by self-gravity (Burns 1998); 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 a ellipsoid-shaped rubble-pile asteroid and the Earth. After an encounter, many of the simulated asteroids develop the same rotation rate and distinctive shape (i.e., highly elongated with a single convex side, tapered ends, and small protuberances swept back against the rotation direction) as 1620 Geographos. 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, which suggests that it too may have been molded by tides in the past.

*Subject headings:* asteroids, dynamics, celestial mechanics
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., 1995a, Ostro et al., 1995b, Hudson and Ostro 1994, Hudson and Ostro 1995, Hudson and Ostro 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 which has been significantly manipulated by planetary tidal forces.

1620 Geographos is an S-class asteroid with a mean diameter slightly over 3 km. It was observed with the Goldstone 2.52-cm (8510-MHz) radar from August 28 through September 2, 1994 when the object was within 0.0333 AU of Earth (Ostro et al., 1995a, Ostro et al., 1996). A delay-Doppler image of Geographos’s pole-on silhouette (Fig. 1) showed it to have more exact dimensions of $5.11 \times 1.85$ km ($2.76 \times 1.0$, normalized), making it the most elongated object yet found in the solar system (Ostro et al., 1995a, Ostro et al., 1996). In addition, Geographos’s rotation period ($P = 5.22$ h) is short enough that loose material is scarcely bound near the ends of the body (Burns 1975). For reference, Geographos would begin to shed mass for $P \lesssim 4$ h if its bulk density was 2.0 g cm$^{-3}$ (Harris 1996; Richardson et al. 1998).

EDITOR: PLACE FIGURE 1 HERE.

Geographos’s elongated axis ratio was unusual enough that Solem and Hills (1996) first
hypothesized it may not be a consequence of collisions. Instead, they speculated 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 non-rotating strengthless spherical aggregates making close slow passes by the 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 and 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 really make the case that 1620 Geographos is a tidally distorted object, several questions must be answered:

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

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

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

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

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

In the following sections, we will address each of these questions in turn. Our primary tool to investigate these issues is the $N$-body code of Richardson et al. (1998), more
advanced than the code of Solem and Hills (1996) and capable of determining the ultimate shape and rotation of our progenitors. 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, in general, 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 km-sized asteroids (and comets) are weak “rubble-piles”, aggregates of smaller fragments held together by self-gravity rather than material strength (Chapman 1978, Love and Ahrens 1996). We list a few salient points; additional information can be found in Richardson et al. (1998). (i) Comet Shoemaker-Levy-9 (SL9) tidally disrupted when it passed within 1.6 planetary radii of Jupiter in 1992; numerical modelling suggests this could only have happened if SL9 were virtually strengthless (Asphaug and Benz 1996). (ii) C-class asteroid 253 Mathilde has such a low density (1.3 g cm\(^{-3}\); Veverka et al., 1998) compared to the inferred composition of its surface material (i.e., if carbonaceous chondrite-like, it would have a density \(\sim 2\) 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. (iii) 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 h; this spin rate matches where rubble-pile bodies would begin to fly apart from centrifugal forces (Harris 1996). (iv) Most collisionally evolved bodies larger than \(\sim 1\) km are highly fractured, according to numerical simulations of asteroid impacts (Asphaug and Melosh 1993, Greenberg et al., 1996, Love and Ahrens 1996). (v) 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 their internal structures are so broken up that they damp the propagation of shock waves and thereby limit 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 the above 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 which allow them to encounter multiple planets and the terrestrial planet region is crisscrossed with secular and mean-motion resonances (Froeschlé et al., 1995, Michel et al., 1997). For these reasons, it is impossible to accurately 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 et al., (1996), we used a Bulirsch-Stoer variable step-size integration code, optimized for dealing accurately with close encounters, to track the evolution of 8 Geographos-like test clones. We integrated the nominal orbit with $a = 1.246$ AU, $e = 0.335$, $i = 13.34^\circ$; 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 v2.60 (Giorgini et al. 1998). 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 $\nu_{13}$ and $\nu_{14}$ involving the mean precession frequencies of the nodal longitudes of Earth and Mars’s orbits (Michel and Froeschlé 1997, Michel 1997). We found that 5 of the 8 clones (62.5%) had their inclinations increased by these resonances. This trend opens 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, 6 of the 8 clones (75%) had their orbital eccentricities increased by the $\nu_2$ and $\nu_5$ secular resonances with Venus and Jupiter. Lower eccentricities and inclinations in the past imply that close approaches near 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 (Froeschlé et al., 1997). 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 and Hills (1996)), we have used a sophisticated N-body code to model Earth flybys of spherical-particle aggregates (Bottke et al., 1997, Bottke et al., 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 described in Richardson et al. (1998). For brevity, we only review the basics here.

The particles’ motions are tracked during the encounter using a 4th-order integration scheme that features individual particle timesteps (Aarseth 1985). This method allows us to treat interparticle collisions rigorously, with a coefficient of restitution included to produce energy loss (i.e., friction); 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 and Benz 1996).

The code is capable of modelling tidal disruption over a range of rubble pile shapes, spin rates, spin-axis orientations, and hyperbolic trajectories. To verify the code was accurate enough to realistically model shape changes, we consulted two experts in granular media, J. Jenkins of Cornell University, and C. Thornton of Aston University, UK. Based on their suggestions, we checked our code against some standard diagnostic tests in their 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 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, though 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 $v_{\infty}$ (between 1.0 and 32 km s$^{-1}$), rotation period $P$ (tested at $P = 4, 6, 8, 10,$ and $12$ h for prograde rotation, $P = 6$ and $12$ h 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, especially those pertaining to Geographos, below.
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”, a “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. Less severe disruptions were classified as “B”, break-up 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 rubble pile’s axes after encounter (\(a_1 \geq a_2 \geq a_3\)), 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” (\(\varepsilon_{\text{rem}} \equiv 1 - \frac{1}{2}(q_2 + q_3)\)). For reference, our progenitor has \(\varepsilon_{\text{rem}} = 0.43\) and Geographos has a value of \(\varepsilon_{\text{rem}} = 0.64\).

Sampling a broad set of parameters to map tidal disruption outcomes, Richardson et al. (1998) identified 195 S, B, or M-class events produced with a \(\varepsilon_{\text{rem}} = 0.43\) rubble pile. Fig. 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 2 of the 79 outcomes are likely to have a Geographos-like elongations (\(\varepsilon_{\text{rem}} > 0.60\)).
The mean value of $\varepsilon_{\text{rem}}$ 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 $\varepsilon_{\text{rem}}$ values. The mean value of $\varepsilon_{\text{rem}}$ 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 $\varepsilon_{\text{rem}}$ 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. Fig. 2 shows 23 of 76 M-class events with Geographos-like $\varepsilon_{\text{rem}}$ values. Overall, the 76 outcomes have a mean $\varepsilon_{\text{rem}} = 0.54$ with $\sigma = 0.10$. Thus, getting a Geographos-like ellipticity from a M-class disruption is less than a $1 \sigma$ event, decent odds if such disruptions (and $\varepsilon_{\text{rem}} = 0.43$ progenitors) are common.

### 4.4. Spin-up and 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 non-spherical 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. Fig. 3 shows the spin periods of the remnant rubble piles ($P_{\text{rem}}$) for the 195 disruption cases described above. Recall that the range of starting $P$ values was 4, 6, 8, 10, and 12 h for prograde rotation, $P = 6$ and 12 h for retrograde rotation, and the no-spin case $P = \infty$. 
The mean spin period for 79 S-class outcomes is $5.6 \pm 2.2$ hours, while the comparable value for the 40 B-class and 76 M-class events is $5.2 \pm 1.1$ and $4.9 \pm 1.1$ hours, respectively. Note that these last two values are close to the real spin period of Geographos (5.22 h). These similar values indicate that mass shedding only occurs when the km-sized bodies are stretched and spun-up to rotational break-up 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 Fig. 3 do show some scatter, the 195 disruption events together have a mean $P_{\text{rem}}$ value of $5.2 \pm 1.7$ hours, a good match with Geographos once again.

4.5. Matching the shape and spin of 1620 Geographos

Now that we have found tidal disruption outcomes which match Geographos’s ellipticity and spin rate, we can take a closer look at the resultant shapes of the rubble piles themselves. Our goal is to find distinctive features which match comparable features on Geographos, and which are possibly antithetical with 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). Fig. 4 shows this body going through a M-class event with the following encounter parameters: $P = 6$ hours prograde, $q = 2.1R_⊕$, and $v_\infty = 8$ km s$^-1$.
Fig. 4a shows the asteroid before 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 gravity, tidal, and centrifugal terms. At this stage, it hugs the outer surface of the rubble-pile.

Fig. 4b shows the body shortly after perigee passage. Here, the equipotential surface becomes a more elongated ellipsoid with its longest axis oriented towards Earth. Differential tidal forces, greatest at perigee, and centrifugal effects combine to set the particles into relative motion, producing a landslide towards 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 the Earth stretches the model asteroid and, by 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.

Fig. 4c shows the latter 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 as 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 bow-like. This effect produces a convex surface along the long axis and a “hump”-like mound of material on the opposite side.

Fig. 4d shows the final shape of the object. The spin ($P_{rem} = 5.03$ h) and ellipticity ($\varepsilon_{rem} = 0.65$) are virtually identical to 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  \cite{Hamilton1996}, such that some particles lie further 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, 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 to the stubbier antipode. The overall final shape of the body is much like that of a “porpoise” or “schmoo”. A comparison between Fig. 1 and Fig. 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 of Bottke et al. \cite{Bottke1998} and combine a “map” of tidal ellipticity results (described in 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 \cite{Richardson1998}. Similarly, this same body should get a Geographos-like ellipticity \( \varepsilon_{\text{rem}} > 0.60 \) once every \( \sim 560 \) Myr. The most likely disruption candidates have low \( e \)'s and \( i \)'s, consistent with the Geographos’s probable orbital history (i.e., Sec. 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 \( \sim 15\% \) of all ECOs undergo S-, B- or M-class disruptions (i.e., 10 Myr / 65 Myr), and that \( \sim 2\% \) of all ECOs (i.e., 10 Myr / 560 Myr) should have shapes (and spins) like Geographos. The implications of this prediction will be 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 \( H = 15.6 \) (Giorgini et al. 1998). Morrison (1992) estimates 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 2 objects, it is perhaps not surprising 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 when one considers that only 35% of the \( H < 15.0 \) ECOs have been been discovered, and 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 towards objects which pass near the Earth on low inclination orbits (Jedicke 1996), exactly the class of objects which are favored to undergo tidal disruption. Hence, the discovery of Geographos’s shape among a limited
sample of ECOs may not be a fluke. We predict, though, that more Geographos-like objects are lurking among 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 asteroid, 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 hours) and a highly elongated shape ($36 \times 15 \times 13$ km; $2.77 \times 1.2 \times 1.0$, normalized; ellipticity $\varepsilon_{rem} = 0.61$) (Zellner 1976, McFadden et al., 1989, Mitchell et al., 1998). Both values are comparable to those recorded for Geographos and with 15% (30 out of 195) of our S-, B-, and M-class disruption cases.

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 has a signal to noise ratio of $\sim 70$ while the shape has been “fit” to a reference ellipsoid which can eliminate discriminating features. 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 analogous to similar features on Geographos, themselves produced by spiral deformations associated with tidal forces. Images from the
NEAR spacecraft should readily resolve this issue.

The NEAR spacecraft 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 which can be directly compared to terrestrial rock samples. If the densities of these samples are substantially larger than Eros’ 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. As we will describe below, 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 cusp-like 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 and Melosh (1996) and Richardson et al., (1998) show that asteroids affected by tides may often have small satellite companions which 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 \( (a = 1.46 \text{ AU}, e = 0.22, i = 10.8^\circ) \). Test results show that tidal disruption events occur relatively infrequently near Mars, since it is a weak perturber (Bottke and Melosh 1996). 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 et al.)
Numerical integrations of Eros-type clones show that secular resonances $\nu_4$ and $\nu_{16}$ probably modified Eros’s orbital parameters, decreasing its eccentricity enough to place it out of reach of the 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 km-sized asteroids and comets are rubble piles. When these objects, in the form of ECOs, encounter a planet like the Earth, S-, B-, and M- class tidal disruptions frequently produce elongated objects ($\varepsilon_{rem} > 0.6$) with fast spin rates ($P \sim 5$ hours). These values are consistent with at least two objects in near-Earth space, 1620 Geographos and 433 Eros, which may have made 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 or Venus’s tidal forces resemble the radar-derived shapes of Geographos and 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 recognized important geological process 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 his constructive reviews of this manuscript. PM worked on this paper while holding the External Fellowship of the European Space Agency. DCR was supported by grants from the NASA Innovative Research Program and NASA HPCC/ESS. Preparation
of the paper was partly supported by NASA Grant NAGW-310 to J. A. Burns.
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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 multi-run sums of twelve co-registered 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 central circular arrow. Brightness indicates the strength of radar return, arbitrarily scaled. Despite substantial smearing of the periphery features, some distinguishing characteristics can be observed: (i) The long axis is tapered on both ends, with one tip narrow and the other more pinched and squat. (ii) One side is smooth and convex; the opposite side has a “hump”. (iii) 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 twelve summed co-registered 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, though considerable smearing remains.

Fig. 2.— The ellipticity values of our model asteroids plotted against the fraction of mass shed in each tidal disruption outcome. 79 S-class, 40 B-class, and 76 M-class disruptions are shown. The starting ellipticity for our model rubble pile is $\varepsilon_{\text{rem}} = 0.43$. Geographos’s ellipticity $\varepsilon_{\text{rem}} = 0.64$. Note that most M-class disruptions produce high ellipticities.

Fig. 3.— The 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 h and $P = \infty$ (i.e., no spin). Note that three S-class and one M-class events have final spin periods between 10–20 hours (i.e., beyond our $P = 10$ h plotting limit). Regardless of the starting spin period, most disruptions spin-up the model asteroid to $P < 6$ h.

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

Fig. 5.— Pole-on silhouette of Eros, based on a model where radar data were fit 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. Definitions for center of figure, center of rotation, and rotation direction are given 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).
(a) (b) (c) (d)

Cusp
Convex side
Narrow end (tapered)
Wide end (tapered)
"Hump"
Cusp
Convex side
Narrow end (tapered)
Bent tapered end (0°)

Rounded end (180°)

Side with one (or several?) concavities (270°)

Highly convex side (90°)

Radar

10 km