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Implications of the NEAR mission for internal structure of Mathilde and Eros

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Abstract

The Near Earth Asteroid Rendezvous (NEAR) performed a flyby of the C-type main belt asteroid 253 Mathilde and an orbital study of the S-type near-Earth asteroid 433 Eros. These asteroid datasets provide a basis for inferences regarding physical properties and internal structure. The NEAR flyby of Mathilde revealed a heavily cratered surface with at least five giant craters (close to geometric saturation). Mathilde's density was unexpectedly low at $1.3 \pm 0.3\ \mathrm{g\,cm^{-3}}$, indicating a high porosity. Such a high porosity may be consistent with a rubble pile structure and may favor a compressional style of cratering. There are structural features, such as a 20-km long scarp, and polygonal craters indicating that Mathilde is not completely strengthless. At least one of its structural components appears coherent over a few tens of km. NEARs study of Eros found an average density of $2.67 \pm 0.03\ \mathrm{g\,cm^{-3}}$, almost uniform within the asteroid. Several lines of evidence suggest a globally consolidated internal structure: topographic features indicating tectonic deformations, regional scale linear features with related orientations, and structural control of craters in an intermediate size range. Eros is interpreted to be extensively fractured, but it was not disrupted and reaccumulated gravitationally. Some constraints can be placed on its strength. The consolidated interior must support a shear stress at least on the order of a few bars. Crater morphologies can be interpreted as suggesting a 'strength' near the surface of a few tens of kPa. Macroscopic fractures within Eros should be filled with fines, so the low average density of Eros relative to ordinary chondrites is not simply explained by macroscopic void space.
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Keywords: Asteroids; Asteroids, surfaces; Asteroids, interior structure; NEAR mission

1. Introduction

Current understanding of planetary formation holds that the planets condensed from a disk of gas and dust, initially forming meteoroid-sized to asteroid-sized planetesimals that subsequently underwent collisions, resulting in accretional growth, fragmentation, or breakup, depending on the relative velocities and physical properties of the planetesimals. Many of these planetesimals were incorporated into growing planetary embryos, but the present day asteroid belt is believed to contain examples of remnants – asteroids – representing every stage of evolution from primitive planetesimal to fragments of differentiated proto-planets. By studying the physical properties and internal structures of the diverse populations in the asteroid belt, we may obtain insights into the dynamical processes resulting in planet formation, and particularly the balance between collisional fragmentation and accretion. Signatures of these processes may be preserved in the interiors and in some cases perhaps even the surfaces of primitive bodies.

The first planetary mission dedicated to the study of asteroids was the Near Earth Asteroid Rendezvous (NEAR), and the determination of asteroid physical properties was one of the primary objectives. NEAR was launched on February 17, 1996 and performed the first flyby of a C-type main belt asteroid, 253 Mathilde, on June 27, 1997 (Veverka et al., 1997; Yeomans et al., 1997). NEAR performed a flyby of 433 Eros on 23 December 1998 (Yeomans et al., 1999; Veverka et al., 1999a), and entered orbit around Eros on 14 February 2000 (Yeomans et al., 2000; Zuber et al., 2000; Veverka et al., 2001a; Cheng et al., 2001). After successfully

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completing the first orbital study of an asteroid, the NEAR spacecraft was renamed NEAR Shoemaker (after Eugene Shoemaker, 1928–1997) and accomplished the first asteroid landing, on 12 February 2001 (Veverka et al., 2001b). Results from the NEAR mission at Eros have been collected in special issues of *Icarus* (January, 2002) and *Meteoritics* and *Planetary Science* (December, 2001). A Mathilde special issue of *Icarus* appeared in July, 1999. Recent summaries of NEAR results have been given by Cheng (2002), Chapman (2002) and Sullivan et al. (2002) in the *Asteroids III* volume. The following will summarize implications of NEAR results for internal structure of Mathilde and Eros.

2. Observations at Mathilde and Eros

At Mathilde, NEAR measured the mass (1.03×10^{17} kg) and estimated the volume (Yeomans et al., 1997; Veverka et al., 1997). Although only one face of Mathilde could be imaged during the flyby, the size of the unseen hemisphere could be constrained from ground-based lightcurve observations (Mottola et al., 1995). The measured mass and estimated volume imply a Mathilde bulk density of 1.3 ± 0.3 g cm^{-3}. Comparison to the typical densities of carbonaceous chondrite meteorites implies an internal porosity for Mathilde on the order of 50% (Veverka et al., 1999b). Such a high porosity is within the range suggested for rubble pile asteroids, meaning strengthless gravitational aggregates that possibly formed by collisions which disrupted the parent body without dispersing it (e.g., Richardson et al., 2002). Photogeologic evidence also supports the importance of compression cratering in low-density Mathilde, in which excavation flow is suppressed relative to compaction (Housen et al., 1999). This process may explain how giant craters can be superposed in close proximity as seen on Mathilde.

However, photogeologic evidence from NEAR indicates that Mathilde is not completely strengthless. A 20-km long scarp has been identified as well as polygonal (strength-controlled) craters (Thomas et al., 1999; also see Fig. 1). The significance of a 20-km long structural feature would be that if Mathilde is a rubble pile, at least one of its component bodies appears coherent over scales of 20 km, so a rubble pile Mathilde cannot be formed entirely from small bits of rubble. However, this linear feature is subtle and close to the limit of resolution. Moreover, Mathilde's high porosity does not necessarily imply a rubble pile structure; Mathilde may have accreted originally as a porous, low density object and survived as such to the present (Cheng and Barnouin-Jha, 1999).

At Eros, NEAR returned data from a flyby in December 1998 and a year-long orbit from February, 2000 to February, 2001. The flyby and orbital observations yielded mass and density values of $(6.687 \pm 0.003) \times 10^{15}$ kg and (2670 ± 30) kg m^{-3}, respectively (Yeomans et al., 2000). NEARs instruments provided measurements that indicate Eros is a consolidated body, not a loosely bound agglomeration of smaller component bodies (Veverka et al., 2000; Zuber et al., 2000). The measured gravity field is consistent with a uniform density object of the same shape (Yeomans et al., 2000), although the center of mass may be offset from the center of figure by <1% of the radius (Miller et al., 2002; Thomas et al., 2002). This offset would indicate that the density is not perfectly uniform, and could be accounted

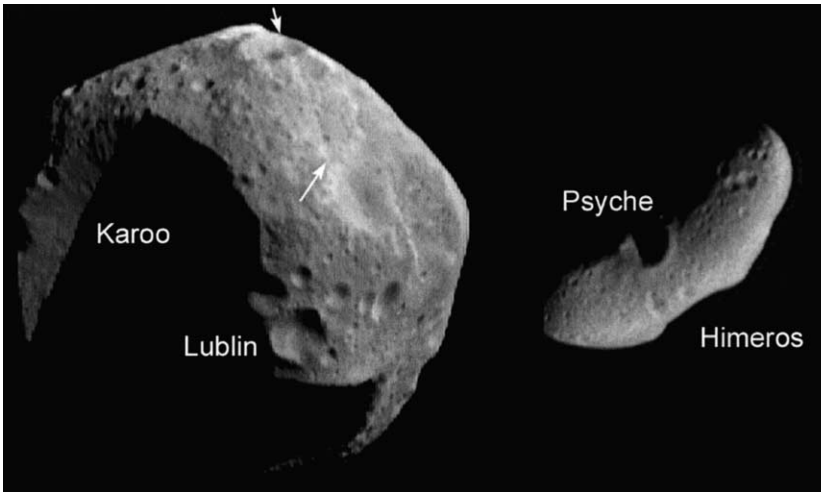

Fig. 1. Mathilde (left) and Eros (right) approximately to scale. Eros is 33 km long and is much brighter (geometric albedo 0.25; Clark et al., 2002) than Mathilde (geemetric albedo 0.05). Two large craters on Eros are called out, Psyche in the western hemisphere and Himeros on the limb in the eastern hemisphere. On Mathilde, the largest known impact crater is Karoo, a fresh-appearing giant crater close to, or superposed upon, other large craters. The crater Lublin is an example of polygonal cratering on Mathilde. The white arrows denote a linear feature on Mathilde that is interpreted as a scarp (Thomas et al., 1999).

for by an underdense regolith layer of up to 100 m depth (Zuber et al., 2000). However, interior density variations, as well as a regolith layer of variable depth, would be possible explanations (Sullivan et al., 2002). Comparisons with the densities of ordinary chondrite meteorites suggest an Eros bulk porosity of about 25%, which would be more consistent with a fractured consolidated body than a rubble pile (Wilkison et al., 2002). However, as will be discussed below, it is not clear whether ordinary chondrites are truly analogous in composition to Eros, nor is it clear whether the inferred porosity is microscopic or macroscopic.

Additional evidence that Eros is a fractured, consolidated body is found in the NEAR images which show linear structural features. These ridges, grooves, and chains of pits or craters display regionally coherent alignments on hemispheric scales (Veverka et al., 2000; Thomas et al., 2002). Examples include the 18 km-long ridge system called Rahe Dorsum (Fig. 2) and the approximately co-planar Calisto Fossae ridge at 25°S, 150°–170°W (Fig. 3). Further evidence of structural strength on Eros is found from crater morphologies. Craters smaller than 1 km but larger than a few hundred meters often appear to be jointed and/or structurally controlled (Prockter et al., 2002), although the largest craters on Eros (such as Psyche) are bowl-shaped. This is interpreted as consistent with presence of a consolidated but fractured substrate covered by a loose regolith to a depth of <100 m, so that craters in a particular size range appear jointed, but much larger or smaller ones do not. Additional evidence for a consolidated substrate is found in the presence of steep slopes which exceed expected angles of repose over a few percent of the Eros surface area (Zuber et al., 2000). Taken together, the gravity field measurements, the linear structural features, the tectonic features such as Rahe Dorsum, the jointed craters, and the indications of internal structural coherence, all suggest that Eros is a collisional fragment from a larger parent body, or a so-called 'collisional shard'.

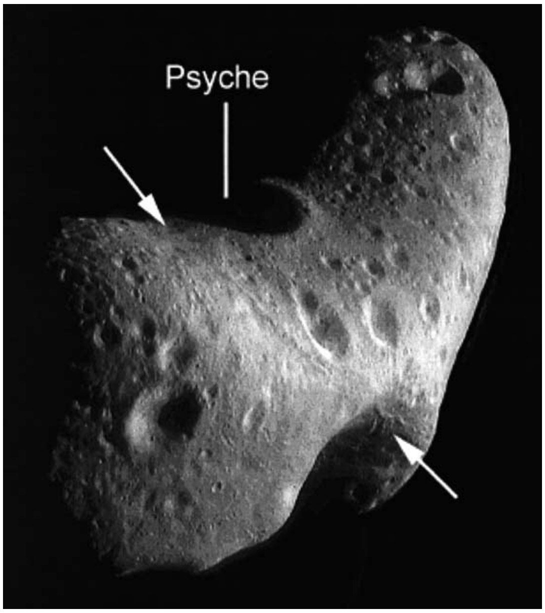

Fig. 2. Eros and a portion of the 18-km ridge Rahe Dorsum (white arrows), which lies approximately in a plane. Crater Psyche is marked.

3. Discussion

The NEAR mission measured the bulk density of Eros but did not make any other direct measurement of internal structure. Inferences concerning internal structure are those made from observations of shape and surface morphology as discussed above. Still, the internal structure of Eros, and specifically the issue of whether it was disaggregated and reaccumulated in its present form, has important implications for the dynamical history of the asteroid belt. However, any connection between the collisional history of Eros in particular, and that of main belt asteroids in general, is complicated or perhaps obscured by the complex orbital history of Eros and its highly uncertain lifetime in orbits

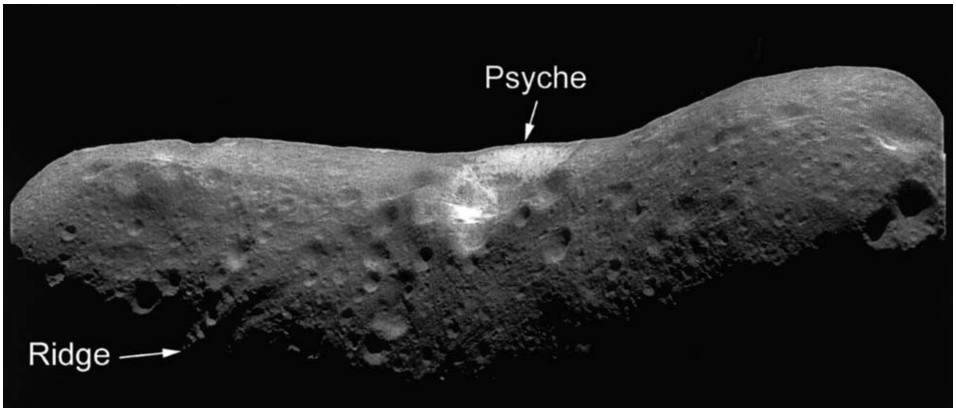

Fig. 3. Eros and linear structural features. The ridge is part of the Calisto Fossae complex, which is approximately co-planar with Rahe Dorsum (Thomas et al., 2002).

similar to its present Earth-approaching orbit (Michel et al., 1998).

Richardson et al. (2002) have recently suggested that a plot of porosity versus a quantity called 'relative tensile strength' (RTS) would be useful to describe the internal structure of asteroids, and specifically to distinguish qualitatively between rubble pile, fractured, and coherent structures. RTS is defined as the ratio of *tensile strength of the asteroid to the mean tensile strength of its components*. Richardson et al. caution that no distinction is made here between micro- and macro-porosity (the latter meaning porosity due to void spaces between components) and note also that the notion of 'component' is unclear (i.e., what is a component, and how can components be defined, even with *in situ* measurements). However, there are additional difficulties with the porosity-RTS construct beyond these theoretical issues.

Despite all the information returned from NEAR about 433 Eros, little can be said about internal structure in the terms discussed by Richardson et al.: Eros cannot be placed in the porosity-RTS plot. Even with Eros porosity constrained in the fairly narrow range 21–33% (Wilkison et al., 2002), we cannot relate this measured value to the regimes defined by Richardson et al., namely, 'impact energy absorbed', 'spalls damped', 'tensile wave suppressed', etc.

Still less can be said about the tensile strength or about RTS, except that there is abundant morphological evidence that Eros is not completely strengthless. The non-spherical shape of Eros implies that the interior must sustain shear stresses on the order of a few bars, at least. In this sense the interior must be consolidated, but its strength may be much less than the strength of competent rock. The rotation of Eros is slow enough that no portion of the interior is under tension. A somewhat more conjectural strength constraint can be obtained from the observation that craters below $\sim$300 m diameter appear bowl-shaped. If this is interpreted as a transition from strength-controlled cratering (for intermediate crater sizes on Eros, Prockter et al., 2002) to gravity-controlled cratering for small craters, then the 'cratering strength' parameter Y would be 18 kPa for a surface gravity of 0.3 cm s^{-2} on Eros (Cheng et al., 2002). However, even if this somewhat indirect constraint is accepted, we should recall that the cratering strength is a measure of resistance to cratering flow but is not simply related to any tensile strength. The inferred 18 kPa cratering strength would be similar to values inferred for typical lunar soils, and suggests that surface materials on Eros may have similar cohesiveness and other mechanical properties to those of lunar regolith.

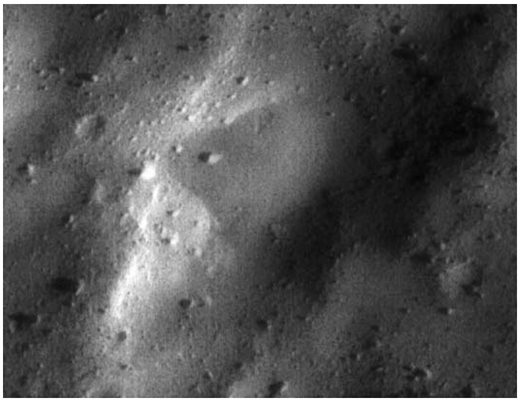

Fig. 4. A pond on Eros, a sharply demarcated, smooth and gravitationally level surface deposit found typically within bottoms of degraded craters. Imaged scene is 300 m across.

The ponded deposits on Eros (Robinson et al., 2001; Fig. 4) may yield additional inferences on interior structure, if they are attributed to seismic shaking from impacts, as suggested by Cheng et al. (2002). In the seismic shaking model, impacts generate seismic accelerations of the surface that induce mass motion, causing unconsolidated materials to pond in gravitational lows. Seismic accelerations on the order of the local acceleration of gravity induce slope failures. As long as seismic shaking persists, the granular surface material can undergo fluid-like motions. A shallow layer of such material, within a confining bowl (a crater) formed in a consolidated substrate, will tend to form a level surface. The time scale for leveling the surface is several times the propagation time of shallow gravity waves across the forming pond. Once the pond surface is substantially level, its intersection with its confining walls forms a sharp boundary. Although the seismic shaking model is tentative, it appears to explain why ponds are found on Eros but not on the Moon (Cheng et al., 2002). Nevertheless, the global propagation of seismic waves, as invoked in the model, puts only weak constraints on interior structure of Eros. Apollo experiments established that seismic waves propagate through the surface layers of the Moon. The required shear strength of the Eros interior is similar to that required to support topography of a few tens of meters on the Moon, and the cratering strength of Eros surface material may be no greater than that of unconsolidated lunar soils.

The issue of how to interpret the Eros density measurement is also key to understanding the internal structure. The average porosity of 25% is inferred from comparison of the Eros density to that of ordinary chondrite meteorite analogs, and it means that bulk Eros has a higher proportion of void space than these meteorites. It is critically important whether the higher porosity of Eros reflects primarily void space between 'components' in the sense of Richardson et al. (2002), or whether the components themselves are more porous than meteorite analogs. In this context, Britt and Consolmagno (2001) proposed that the density of Eros is low compared to meteorite analogs because fines are forced by friction to remain at the surface of Eros, and macroscopic fractures within the asteroid should be empty. In their argument, the forces of gravity and friction on a grain are

$$\begin{aligned} F_{\text{friction}} &= \mu\left(\frac{2\pi}{3}\right)\rho_a^2 G r^2 (R_T^2 - R^2) k_1, \\ F_{\text{gravity}} &= \left(\frac{4\pi}{3}\right)^2 \rho\rho_a G r^3 R k_2. \end{aligned} \qquad (1)$$

In this model, the friction force is related to lithostatic pressure via a friction coefficient μ, while the k_1 and k_2 are geometric constants. The densities of the grain and the asteroid are ρ and ρ_a. Bodies are assumed spherical, with r the grain radius, R distance to the asteroid center, and R_T the asteroid radius. In this model the friction force dominates gravity for small particles (under a meter), and the dominance of friction over gravity increases as the depth increases, so it is concluded that fractures within Eros are empty.

However, these equations do not describe the static equilibrium of the grains self-consistently. An example of a self-consistent calculation is given below. A granular medium is assumed to fill a rigid vessel defined by the walls of a fracture, which here takes the shape of a vertical cylinder of diameter D. The weight of a cylindrical slab of thickness $\mathrm{d}R$ becomes $\rho g(\pi D^2/4)\,\mathrm{d}R$, where the acceleration of gravity in the spherical body is $g = 4\pi G\rho R/3$. The weight is balanced by the pressure gradient force $-(\pi D^2/4)\,\mathrm{d}P$ and the friction force $\mu P\pi D\,\mathrm{d}R$, so the equilibrium equation is in the same notation

$$\frac{\mathrm{d}P}{\mathrm{d}R} = -\rho g + \frac{4\mu P}{D}. \qquad (2)$$

If g is a constant independent of depth, this equation is well known to predict that the pressure in the granular medium approaches a constant value at large depth ($\gg D/4\mu$). This behavior of the granular medium contrasts with that for a fluid, in which the pressure increases continually with depth. For the present example of a spherical asteroid with a stress-free surface at $R = R_T$, the pressure in the granular medium becomes

$$P = \frac{\pi G\rho^2 D}{3\mu} \times \left[R + \frac{D}{4\mu} - \left(R_T + \frac{D}{4\mu}\right)\exp\left(\frac{4\mu}{D}(R - R_T)\right)\right]. \qquad (3)$$

The pressure variation with depth is qualitatively different from that assumed in Eq. (1), which is $P \propto (R_T^2 - R^2)$. In fact, the granular medium model (3) predicts that the pressure reaches a maximum at a shallow depth of several times $D/4\mu$, below which depth the pressure *decreases* towards the center of the asteroid. The pressure of Eq. (3) varies roughly linearly with radius over almost the entire volume of the asteroid. Since by assumption $D \ll R_T$ in this model, the granular medium pressure from Eq. (3) is much smaller than from Eq. (1) for most of the asteroid volume. The pressures from Eqs. (1) and (3) are similar only close to the surface, at shallow depths $\ll D/4\mu$.

The point is that within the granular medium, as opposed to the walls of the fracture, the forces of gravity, pressure and friction on a grain must balance self-consistently for static equilibrium, and the friction force does not become dominant. Mechanical equilibrium does not forbid fines from falling into macroscopic cracks within an asteroid. The morphological evidence from the surface of Eros includes examples where fines appear to drain into subsurface fractures (Prockter et al., 2002). Of course, there must be load-bearing structure within Eros, within which the lithostatic pressure must apply as opposed to a granular medium pressure. If Eros has structural components in the sense of Richardson et al. (2002), the lithostatic pressure would apply *within* components whereas a granular medium equation like (2) would apply to fines *between* components. It is argued here that if macroscopic gaps or fractures exist within Eros, they cannot remain empty in the presence of repeated seismic jostling from impacts, but they must become filled with fines. In this case, the low average density of Eros, compared with those of ordinary chondrite meteorites, may reflect a fundamental difference between the structural components of Eros and these meteorite analogs. Perhaps the implication is that these meteorites are not true analogs of the bulk material in Eros.

Although the NEAR data did not clearly identify a meteorite analog for the composition of Eros (McCoy et al., 2001), the Eros composition is at least similar to that of ordinary chondrites, with possible fractionations occurring in the regolith (sulfur depletion in the extreme surface, and iron depletion in ponds; Evans et al., 2001). The average density of Eros is close to measured densities of achondrites and falls within the range of densities measured for carbonaceous chondrites, but the visible and near-IR spectra of Eros are not consistent with achondrite or carbonaceous chondrite compositions. Hence, these compositions do not provide a viable explanation for the average density of Eros without appealing to porosity.

4. Summary

The NEAR, mission to Mathilde and Eros has returned a wealth of information but has only sharpened questions about interior structure. Mathilde has a very low density and shows evidence of compaction cratering; it may be a rubble pile but at the same time it shows evidence of material strength and of large, coherent structural components. Eros also has a low density compared to those of ordinary chondrites, and it appears to be a fractured body rather a rubble pile, but implications of these observations are unclear. The

Richardson et al. (2002) plot of porosity versus relative tensile strength appears to be useful mainly as a theoretical construct and is not easily related to available observations. Much work remains to be done.

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