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## NEAR at Eros: Imaging and Spectral Results

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Eros is a very elongated (34 kilometers by 11 kilometers by 11 kilometers) asteroid, most of the surface of which is saturated with craters smaller than 1 kilometer in diameter. The largest crater is 5.5 kilometers across, but there is a 10-kilometer saddle-like depression with attributes of a large degraded crater. Surface lineations, both grooves and ridges, are prominent on Eros; some probably exploit planes of weakness produced by collisions on Eros and/or its parent body. Ejecta blocks (30 to 100 meters across) are abundant but not uniformly distributed over the surface. Albedo variations are restricted to the inner walls of certain craters and may be related to downslope movement of regolith. On scales of 200 meters to 1 kilometer, Eros is more bland in terms of color variations than Gaspra or Ida. Spectra (800 to 2500 nanometers) are consistent with an ordinary chondrite composition for which the measured mean density of 2.67  $\pm$  0.1 grams per cubic centimeter implies internal porosities ranging from about 10 to 30 percent.

The Near Earth Asteroid Rendezvous (NEAR), a Discovery spacecraft launched on 17 February 1996, was designed to carry out the first detailed orbital investigation of an asteroid (1). After a flyby of asteroid 253 Mathilde in June 1997 (2) and a swingby of Earth in January 1998, the spacecraft carried out an unintended flyby of Eros, coming within 3800 km on 23 December 1998 (3). Data important to the detailed planning of the subsequent orbital mission, such as the mass,

dimensions, and spin state, were obtained during this flyby (3). Shortly after, on 3 January 1999, a burn was executed to slow the spacecraft's speed relative to Eros from about 1 km/s to only 10 m/s, resulting in a year-long, gradual return to the asteroid. The spacecraft was inserted successfully into an initial orbit around Eros on 14 February 2000.

Eros, discovered in 1898, was the first asteroid found to cross the orbit of Mars and was the first asteroid detected to show periodic brightness fluctuations, which were soon attributed correctly to its elongated shape and a rapid rotation of 5.27 hours (4). The orbital path of Eros takes it from 1.13 astronomical units (AU) close to Earth's orbit to beyond the orbit of Mars at 1.73 AU, every 1.76 years (5). Spectrally, Eros is classified as an S-type asteroid, the type common in the inner portions of the asteroid belt, the surface mineralogy of which is apparently dominated by silicates (pyroxene and olivine) and Fe-metal (6, 7).

NEAR was designed to carry out a global survey of the surface properties and internal structure of Eros (1). This report is based on data obtained by the NEAR camera [the mul-

standing efforts in making the NEAR-Shoemaker mission an unqualified success. A portion of the research reported in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA.

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tispectral imager (MSI)] and the NEAR infrared spectrometer (NIS) through the first month and a half of orbital operations from 14 February to 1 April 2000. Details of these instruments have been described previously (8, 9). The majority of the imaging data presented were obtained from a 200-km orbit at a phase angle of about 90° and a nominal resolution of about 25 m/pixel. Immediately before orbital insertion, on 12 to 13 February, NIS obtained spectra at spatial resolutions of about 1 km under high sun lighting conditions (phase angles as small as 1°). Because shadows are minimized, such conditions are ideal for spectral mapping. A preliminary analysis of these data is included here. Because NEAR does not have a scan platform and must keep its solar panels pointed within 50° of the sun, it was not possible for MSI to image Eros at the same time that NIS was taking low-phase spectra: NIS has a scan mirror allowing it to look off axis, but MSI does not (8, 9).

**Global properties.** Regular observations of Eros began in mid-December 1999, when the range decreased below 100,000 km and the MSI camera began to resolve the asteroid (resolution = 12.5 km/pixel at 100,000 km). An intensive search for satellites out to 100 asteroid radii was performed during the approach. Our satellite search reached an approximate limit of V-magnitude +8.5, corresponding to objects of about 20-m diameter (assuming an albedo equal to that of Eros). No satellites were found. To date, 243 Ida and 45 Eugenia remain the only two asteroids known to have satellites (*10*).

The rotation pole of Eros is inclined by 88° to the normal to the orbital plane (11). When NEAR flew by Eros in December 1998, the southern high latitudes of the asteroid were in daylight. By February 2000, the sun was at high northern latitudes, with the north polar region completely illuminated. The flyby data of December 1998 produced complete coverage of Eros south of latitude 20°N at resolutions of 400 to 800 m/pixel; the early orbital data in February and March 2000 yielded complete coverage of the northern hemisphere with some glimpses down to 40° to 50°S, at resolutions of  $\ge 25$  m/pixel.

Two views of Eros are shown in Fig. 1. The asteroid's elongated shape is not markedly determined by obvious large craters or impact scars. At a resolution of 25 m/pixel, the view is dominated by craters 0.5 to 1 km across. The largest features (Fig. 1) are a

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5.5-km crater and an irregularly shaped depression (termed the "saddle" hereafter) some 10 km across.

By combining coverage of the southern hemisphere obtained during the December 1998 flyby with imaging of the northern hemisphere obtained in early 2000, it is possible to construct a complete three-dimensional model of the shape of Eros (Fig. 2 and Table 1). A coordinate system was defined (Fig. 3), with longitude increasing to the west from a prime meridian through a prominent crater (as yet unnamed) that lies approximately in the plane defined by the asteroid's *a* and *c* axes (Fig. 3). The rotation pole of Eros and its orientation have been determined by tracking landmarks (Table 1).

The shape of Eros (Fig. 2) has been determined from stereogrammetric control point solutions that include body-centered positions as well as the asteroid spin vector. The solution uses 12,026 measurements of 2106 points in 774 images. The spin pole solution (right ascension =  $11.4^{\circ}$ , declination =  $17.3^{\circ}$ ) is consistent with an independent NEAR determination in (12, 13) and with previous Earth-based results (11). The control points define the shape of the asteroid north of about 20°S latitude. Low-resolution data from the December 1998 flyby help constrain the shape of the far southern hemisphere. The volume derived from MSI images is closely similar to that derived by the Radio Science team by combining data from MSI and the NEAR laser rangefinder (NLR) (12, 13). Combining the volume listed in Table 1 with the mass of Eros obtained by the Radio Science team (12, 13) yields a mean density of 2.67  $\pm$  0.1 g/cm<sup>3</sup>. At this early stage of the NEAR orbital mission, it is not possible to determine the composition of Eros in a definitive way. Bulk porosity would range from 10 to 30% for a chondritic composition to 40 to 50% for stony irons (14). If one assumes a uniform density for the asteroid, the current shape determination shows that the two smaller principal moments of inertia are sufficiently different to exclude the possibility that Eros is close to a state of unstable rotation (15).

The shape and the mass permit calculation of the surface acceleration vectors that result from self-gravity and spin. The elongated distribution of mass and the greater rotational effects at the ends cause the effective topography (*16*) to be muted compared with the asteroid's radii. Effective topography on Eros has a range of only about 2 km. The highest areas are near the long ends of the asteroid and at the eastern edge of the "saddle." The lowest are near 100°W in the 5.5-km crater and vicinity (Fig. 4). Slopes, calculated relative to the local gravity vector, are typically less than 20°, consistent with values found on other small objects (*17*), which generally are below typical angles of repose of granular materials ( $\sim$ 35°). The steepest regional slopes on Eros, up to 25°, occur within the 10-km saddle (longitude 270° to 300°W). Average surface gravity on Eros is low (Table 1), less than 10<sup>-3</sup> g, and varies over the asteroid because of the elongated shape and rapid rotation. Escape velocities are a few meters per second and depend substantially on location and direction of motion relative to the local normal (Table 1).

Lineations: Grooves and ridges. A vari-

ety of lineations, such as grooves and ridges, occur on the surface of Eros. The lineations include subtle alignments of sections of the terminator, chains of craters, sinuous and linear elongated depressions, and topographic ridges. The depressions have maximum depths of a few tens of meters and reach 200 m in width and over 2 km in length. With the sun at high northern latitudes, detection of east-west-trending lineations was enhanced in the early orbital views. The shape model



Fig. 1. (A and B) Two global mosaics of Eros from images obtained on 2 February 2000 (range = 350 km; phase = 95°). The resolution is about 25 m/ pixel. In these views, Eros is about 30 km across. The large saddlelike depression (top, left) is about 10 km wide and is located near longitude 270°W. The other side of Eros is dominated by a large 5.5-km crater (bottom, center) near longitude 90°W. Conspicuous brightness variations on the inner walls of craters are evident at lower left. Mosaics constructed from DOY054 images 126712174 262, and 438 and 126721678, 766, and 942. NEAR MSI images are identified by "day of year" (DOY) and "mission event time" (MET).



**Fig. 2.** Shape model of Eros derived from MSI images. The maximum dimension is 34 km. The indentations in the asteroid shape made by the two largest depressions (saddle and 5.5-km crater) are visible in the north polar view at lower right. Evidence of the saddle is also apparent on the right of the  $(0^{\circ}, 180^{\circ}W)$  view at lower left. The panel at upper right shows the gridded shape model superimposed on DOY044 image 125829655 (range = 967 km; phase = 50°).

distinguishes the subtle ridge noted in the flyby images of December 1998 that extends for much of the length of the asteroid from longitude  $180^{\circ}$  to  $360^{\circ}$ W. This ridge has a width of 1 to 2 km and a height of less than 200 m.

By far, the most striking lineament on Eros is a prominent, complex ridge that spans

much of the northern hemisphere. This prominent feature (Figs. 4 and 5) is actually a series of segments strung over  $\sim 15$  km. The segments are typically less than a few tens of meters in height and mostly <300 m across. Near 50° longitude, this ridge becomes several smaller, parallel ridges before terminating in an area of crossing ridges within some-



**Fig. 3.** Cartography of Eros. A simplified grid derived from the shape model is shown superimposed on representative global views of Eros. Longitude is measured west; the zero meridian is defined to pass through a conspicuous crater (0°, 25°) marked by arrow and shown in detail in Fig. 11. Images used are (top left) (126711646, 734, and 910), (top right) (126723790, 3878, and 4054), (bottom left) (126714022, 286, and 374), and (bottom right) (126721942, 2206, and 2294).

Fig. 4. (A) Map of gravitational topography (16) ranging from reds (high) to blues (low), assuming a homogeneous density for Eros and accounting for rotation. An object on Eros would tend to move downhill from a red area to a green or blue region. (B) Map of major lineations and blocks: ridges (green), grooves (red), and blocks (blue). (C) Global mosaic of Eros constructfrom ed images 128242563, 630, 697, 764, 831, and 898, obtained on 12 March 2000 (range = 207)km; phase  $= 93^{\circ}$ ). The images have been filtered to enhance topographic detail. Resolution is 20 m/pixel.



A complex system of ridges, grooves, and lineations transects the large saddle depression. Although the general trend is from lower right to upper left (SE to NW), other less well-expressed trends exist. Some lineations are grooves; others are ridges. Details of the morphologies of key features are shown in Fig. 5. Also visible in Fig. 4 are isolated positive relief features, often occurring in groups, which are most likely blocks of ejecta 40 to 80 m wide (see Fig. 8).

what smoother terrain. This ridge system nearly defines a planar slice through the asteroid, with a normal at about 50°, 145°W (Fig. 6). The morphology of the majority of the ridge is suggestive of compression. Both termini transition to a series of en-echelon troughs—a morphology consistent with a shift from a compressional to a tensional regime. The ridge may represent failure along weaker orientations caused by a large impact.

The pattern of the narrow lineations and their dominant occurrence in one quadrant of the asteroid suggest formation by a specific event or their exposure by resurfacing in a limited area of the asteroid. The lineations fall largely within a region of reduced crater density, within and west of the saddle. Orientations include at least two sets of roughly parallel members, one nearly north-south trending and the other at about 40° to the equator (Fig. 6). Many of the lineations in and west of the saddle (Figs. 4 and 6) are in orientations nearly parallel to the plane defined by the ridge system. It has been suggested that groove-like lineations on small satellites and asteroids can be produced by severe impacts (18). Although many of the lineations seen on Eros are similar to features observed previously on Phobos and Gaspra, the spiral pattern of linear depressions evident in Fig. 7A is unusual and puzzling.

The lineations evident on Eros strongly suggest a pervasive fabric. We suspect that this fabric was induced by the extended history of collisions that Eros has suffered. The fact that the prominent ridge system cuts across structures as large as the saddle suggests that most of these events occurred when Eros had nearly achieved its current shape. We find no persuasive evidence that any of the fabric betrayed by the lineations need be attributed to stratigraphic or compositional layering. The crossing patterns of lineations documented in an area near the saddle (Figs. 4 and 6) suggest that the lineations cannot be attributed to a single cause or event.

A major puzzle concerns the nature and origin of the complex saddle-like feature. Does the concavity seen on the surface of Eros today represent the result of a single event? How is this event related to the cratering history of Eros, and is it possibly related to the formation of the large 5.5-km crater on the opposite side of the asteroid? From inspection of lineations, grooves, and ridges observed in the region of the saddle, it appears that at the time that the saddle was formed, Eros already had a heavily cratered surface and a fabric that was created internally by impact related fractures. It is also evident that some structures, especially the 15km ridge, postdate the formation of the saddle. A detailed sequence of events remains to be worked out. It is interesting to note that large craterlike concavities, which lack the

circular symmetry of smaller impact craters, also occur on asteroid Ida (17) and that a small ridge showing evidence of a compressive event was noted on Gaspra (19).

**Craters and crater ejecta.** The 5.5-km crater (Fig. 8) and the 10-km saddle are not unprecedented in size relative to the mean radius of the body. Impact features as large as 1.5 times the mean radii of small bodies have been noted (17). Impact features equally deep relative to the average radius of the target body have been observed on Deimos and on Ida (20).

Modeling by Asphaug *et al.* (21) suggests that for impacts that occurred when Eros was still within the main belt and for gravity-dominated cratering, projectiles may be 20 to 50 times smaller than the resulting crater. Thus, the 5.5-km crater might have been made by an object less than 300 m across and the saddle, if caused by a single impact, by one less than 500 m across. The excavated volume within the saddle is about 70 km<sup>3</sup>.

Small, positive relief features (Fig. 9), isolated and in groups, are common but nonuniformly distributed on Eros (Fig. 6). Presumably blocks of ejecta, they are visible down to the limit of resolution (20 to 30 m); the largest identified, some 110 m across, is located within the 5.5-km crater (Fig. 8). The blocks are not uniformly distributed with longitude; instead, a strong concentration of blocks occurs in the complex depression west of the saddle (Fig. 9, inset). The distribution of blocks (Fig. 6) shows a low density at high northern latitudes. The blocks do not seem to have collected in low lying areas of the asteroid (Fig. 4). No evidence of downslope movement of boulders, such as downslope tracks, is visible in the available images. Although lineations occur in the vicinity of many blocks, they show no evident association with individual blocks.

The sizes and numbers of blocks on Eros are consistent with findings on another S-type asteroid, Ida, and with observations of Phobos and the moon (22). From the empirical relation between the largest block sizes and crater diameter on the moon, Phobos, Deimos, and Ida (23), the 5.5-km crater could be the source for most of the blocks seen on Eros. The observed distribution of blocks may in part reflect a concentration due to sweeping up of ejecta in low, temporary orbits as suggested for Ida (24). For Eros, this possibility remains to be tested by modeling. The association of the region of highest block density with the area that shows the lowest crater density (see below) may indicate that some blocks may have been exposed by the shifting of previously emplaced regolith.

There are several indications in the MSI images that the asteroid is covered with regolith. The most obvious clue is the abundance of ejecta blocks; a less conclusive clue



Fig. 5. Details of ridges and lineations on Eros. (A) End of ridge near the 5.5-km crater. The ridge divides into several parallel segments and then fades into a crossing set of ridges. From DOY082 image 129143020, centered at 30°N, 42°W. (B) Mid part of ridge, from DOY080 image 128933128, centered at 55°N, 355°W. (C) Grooves west of the saddle area, from DOY072 images, centered at 21°N, 350°W. (D) End of ridges in the saddle-shaped feature. The ridge splits into smaller splays. The ridge in all the images is less than 100 m in height. From DOY072 images, centered at 41°N, 271°W.

Fig. 6. Sketch map of Eros locating the prominent ridge system, the lineations, and the most conspicuous blocks. The outlines of the saddle (left) and 5.5-km crater the (right) are shown. The prominent ridge can be traced for about 15 km on Eros. Although latitudes south of about 30°S remain to be im-



aged at adequate resolution, coverage of the north is complete. The relative paucity of blocks at high northern latitudes and near longitude 180°W is evident. Letters locate individual images in Fig. 5.

Table	1.	Eros	globa	l pro	perties
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Triaxial ellipsoid fit diameters	34.4, 11.2, 11.2 (±0.2 km)		
Minimum diameter	8.7 km (12°N, 102°W		
Maximum diameter	31.6 km (2°N, 176°W)		
Surface area	$1106 \pm 20 \text{ km}^2$		
Volume (MSI data)	2507 ± 40 km <sup>3</sup>		
(Yeomans et al.)* (12)	$2550 \pm 100 \text{ km}^3$		
Density†	$2.67 \pm 0.10 \text{ g/cm}^3$		
Spin pole	$RA = 11.4 \pm 0.1^{\circ}$		
	$DEC = 17.3 \pm 0.1^{\circ}$		
Effective topography‡	2.0 km		
Escape velocity	3 to 17 m/s		
Gravitational acceleration	0.23 to 0.56 cm/s <sup>2</sup>		

\*Yeomans *et al.* (*12*) incorporate NEAR NLR data into their volume determination. †Using mass and volume from Yeomans *et al.* (*12*). ‡See (*16*) for definition of effective topography.





Fig. 7. (A) Densely cratered portion of Eros. The mosaic made from DOY076 images 128615086 and 5646 (range = 190 km; phase =  $81^\circ$ ). A regional pattern of lineations and groove-like depressions defines a spiral pattern trending from upper right to lower left. (B)

Mosaic of Eros showing the sparsely cratered area northwest of the saddle. This mosaic is constructed from DOY062 images 127389968, 90092, 90154, 90216, 90270, and 90340 (range = 230 km; phase =  $92^\circ$ ).

Fig. 8. (Top) Detailed view of the 5.5-km crater. At least two sets of lineations are evident, one set cutting the eastern (right) rim of the crater. The lineations trending at right angles represent the termination of the saddle ridge shown in Fig. 4 (see Fig. 5A). Conspicuous albedo markings, possibly related to slumping material down the inner crater walls, are evident. A number of blocks occur in this area; the largest on the crater floor is 110 m wide. This crater is about 900 m deep. The inner crater wall shows hints of lineations that may continue the trend of one of the groove sets. From DOY084 images 129276866, 6910, 7130, and 7174. (Bottom) Sketch map showing the trend of the two sets of lineations and locations of prominent blocks (black squares). Albedo boundaries within the crater are outlined by dashed lines. Thin continuous lines indicate the most prominent lineations.



is the light markings within certain craters, markings that suggest the movement of regolith down crater slopes. The presence of an asteroid-wide regolith is also consistent with the sharp opposition surge detected by the NIS observations and previous telescopic measurements (25). Depth-to-diameter ratios of a number of prominent craters, determined from shadow measurements (Table 2), range from 0.12 to 0.16, consistent with values from craters of similar diameters on other asteroids (26). Fresh craters on the moon of comparable size have somewhat greater depth-to-diameter ra-

tios of about 0.2 (27). This difference is not surprising. Our sample does not consist of "fresh" craters, and we should expect lower values because of both rim erosion and the infilling of the crater cavity due to later cratering events on the surface of Eros. The depth of the 5.5-km crater, listed in Table 2, is about 0.9 km, close to the lunar value.

We measured the positions and sizes of all craters larger than about 1 km in diameter on the illuminated northern hemisphere of Eros and sampled the population down to 100 m in two selected areas. The first area is a typical heavily cratered portion of Eros centered on (30°N, 130°W). The second area is the sparsely cratered, boulder-rich region north and west of the saddle. Most of the northern hemisphere of Eros shows crater densities (Fig. 10) close to the empirically determined saturation limit typical of heavily cratered terrains on the moon and various planetary satellites (28). The observed size distribution of craters is consistent with the same population of impactors that formed craters on other inner solar system objects, including the moon, Mars, and several asteroids (28). The observed population of craters 1 km or smaller on Eros is similar to those found on Ida and Mathilde but is substantially higher than that on Gaspra (29). However, Eros is undersaturated with craters 2 km in diameter or larger. Unlike other well-observed asteroids, Eros exhibits at least one area, the saddle and regions immediately to the north and west (Fig. 7B), in which crater densities are lower than average by at least a factor of 10 (Fig. 10), indicating that the current appearance of the surface in these areas has been determined by processes other than impact excavation.

One unusual feature of the kilometer-sized craters on Eros is that they sometimes show prominent markings on their interiors; they of-

ten have brighter interior walls and darker floors relative to the surroundings (Figs. 8 and 11). One possibility is that fresher or brighter Latitude (°N) Longitude (°W) Diam

Latitude (°N)	Longitude (°W)	Diameter (km)	Depth (km)	Depth/diameter
5.73	11.84	1.09	0.14	0.12
-24.97	103.33	0.76	0.13	0.16
-8.99	190.31	0.65	0.10	0.16
-9.43	182.40	1.52	0.18	0.12
-4.96	185.92	0.63	0.08	0.13
-4.65	180.41	0.76	0.11	0.14
23.03	38.48	0.91	0.11	0.12
18.94	7.69	2.61	0.38	0.14
32.0	95.0	5.50	0.90	0.16

Fig. 9. Complex topography with numerous ejecta blocks just west of the saddle. The mosaic was made from DOY063 images 127505146, 208, 270, 394, and 456 (range = 205 km; phase = 85°). The resolution is about 20 m/pixel. The inset shows another view of the double depression in which blocks are concentrated. Most of the blocks visible in this view range from 30 to 80 m across. Note the albedo markings evident in craters at upper left.

Fig. 10. Spatial density of craters of different sizes on Eros compared with other asteroids. The red symbols represent measurements of two kinds: (i) counts of all craters larger than about 800-m diameter from visible parts of the northern hemisphere during approach imaging on DOY 043 and (ii) counts of craters 100- to 800-m diameter in a heavily cratered region centered near (30°N, 130°W). bars indicate Error counting statistics. The dashed horizontal line shows the upper limit to crater densities reached in saturated crater fields on numerous planets and satellites. Summary curves

for Gaspra, Ida, and Mathilde are shown (29).

orbit is being carried out at phase angles near 90°, a geometry not conducive to revealing subtle albedo or color variations.

The spectrum of Eros shows two prominent absorption features at near-infrared wavelengths: an absorption near 1000 nm (Band I) attributed to olivine and pyroxene and an absorption near 2000 nm (Band II) attributed to pyroxene. Subtle variations with rotational phase have been reported in the

downslope movement of regolith. At this time, it is difficult to assign an age to the surface of Eros on the basis of crater counts. Only if the flux of impactors averaged over the age of Eros were known could a minimum age be estimated. Unfortunately, Eros is currently in an unstable, Mars-crossing and Earth-approaching orbit. Numerical estimates suggest that it has been in this situation for less than 10<sup>8</sup> years and perhaps for a much shorter period (5). Presumably, Frag. mathematical the anisteneous for the anisteneous for

for a much shorter period (5). Presumably, Eros spent most of its existence in the asteroid belt. If one assumes (arbitrarily) that Eros was exposed to a flux similar to that of Gaspra (29), then its surface has been accumulating craters for more than  $10^9$  years. Because most of the surface is saturated, only a lower limit is possible.

materials are being exposed on crater walls by

Albedo and spectral properties. The photometric properties of the surface are close to those extrapolated from earlier telescopic measurements. Estimates of the geometric albedo average around 0.25, consistent with values of 0.23 and 0.21 determined for S asteroids Gaspra and Ida, respectively (30). Color variations on Eros appear to be much more subdued than on either Gaspra or Ida (30). None have been confirmed within the visible portion of the spectrum from wholedisk light-curve observations or from resolved imaging at scales of 100 to 200 m. There is evidence of very slight variations in the near infrared around 1000 nm.

MSI observations of the southern hemisphere of Eros yielded a geometric albedo of  $0.27 \pm 0.06$  (3), consistent with a previous telescopic determination of  $0.27^{+0.03}_{-0.06}$  (25, 31). NIS observations down to phase angles of 1° yield a geometric albedo of  $0.27 \pm 0.06$ at 946 nm, corresponding to a value of  $0.25 \pm 0.06$  in the visible.

To date, no evidence of ejecta (other than 30- to 100-m blocks) has been noticed outside of impact craters. Our images show no albedo, color, or morphological evidence of any modification of the surface surrounding craters. The only conspicuous brightness differences (not accompanied by marked color variations) that have been noted occur on the interior crater walls and crater floors. This situation is very different from that documented on the other two S asteroids imaged by Galileo. On both Gaspra and Ida, Galileo found albedo and color differences apparently related to ejecta from impact craters (30). In the case of Gaspra, an obvious correlation between color and topography was evident, with darker, redder materials preferentially accumulating in topographic lows. No similar albedo or color patterns have been identified on Eros so far. However, the mapping from

L 2 km.



position of Band I (6, 32) and in the depth of Band II (33, 34). Low spatial resolution color measurements of southern latitudes on Eros made with spectral filters from 450 to 1050 nm were obtained by MSI during the December 1998 flyby (3). Corresponding data for northern and equatorial latitudes were ac-

quired in early 2000, at spatial scales ranging from 7000 to 180 m/pixel and phase angles of 49° to 55° (Fig. 12). These were complemented by multispectral imaging from the 200-km orbit, at tens-of-meters spatial resolution and phase angles between 73° and 104° (35, 36). The color data were used to calculate the

Fig. 11. Albedo marking on Eros. (A) Eros mosaic from images 125990409, 473, 555, and 619 (range = 320 km; phase = 88°) showing large 2-km crater with prominent albedo marking (upper left). Two closeups obtained under different lighting and viewing conditions are shown in (B) (images 127488708 and 894) and (C) (images 127504836 and 898) (range = 205 km; phase =  $84^{\circ}$ ).





Fig. 12. Eight time steps from the last preorbit insertion multispectral sequence, acquired at a distance of 1800 km, showing Eros every 50° of rotation. The spatial resolution is 180 m/pixel. The top image of each pair is an approximation of true color constructed from 450-, 550-, and 760-nm images, which have been interpolated to 480-, 550-, and 630-nm wavelengths. In the bottom images, the Band I depth is shown in false color overlain on a 760-nm image base. Band I refers to the absorption feature near 1000 nm found in the spectra of S-type asteroids (see Fig. 13).

760/550-nm reflectance ratio and to estimate the depth of Band I (34). Because MSI is not sensitive beyond 1050 nm, the depth of Band I was estimated as

$$D_1 = 1 - (R_{950}/R_{760}) \tag{1}$$

which results in an underestimate. Standard  $D_{\rm I}$  measurements from a full spectrum performed on ground-based Eros spectra (34) suggest that the underestimate amounts to 3 to 4%.

Disk-integrated spectra of Eros (Fig. 13A) show no substantial color variation with rotational phase in the northern hemisphere. The flyby spectra, covering southern latitudes, are nearly identical to approach spectra at visible wavelengths but do exhibit a measureable variability at infrared wavelengths: Specifically, the depth of Band I varies by  $\sim$ 2%. The value of the depth of Band I for the northern hemisphere lies midrange of the southern hemisphere variability. Figure 13A demonstrates the good agreement between our data and the ground-based spectra (34, 37); as expected, the spacecraft data show a steeper slope because they were obtained at higher phase angles (38).

The disk-resolved color images of the northern hemisphere (Fig. 12) show little if any color heterogeneity at visible wavelengths, but  $D_1$  varies by about 10%. Lower  $D_{\rm I}$  occurs in the western hemisphere around the 5.5-km crater and in the interior of the saddle. Larger values of  $D_1$  occur on the 0° and 180° longitude ends and on the ridge immediately east of the saddle.

Variations in  $D_1$  can result from differences in mineralogy, particle size, alterations of these due to space weathering, or photometric effects. NIS observations of the northern hemisphere at low-phase angles do not indicate substantial mineralogic differences, but  $D_1$  decreases with phase angle, suggesting that photometric differences could account for some of the variations seen by MSI. Although the northern hemisphere images (Fig. 12) were taken over a small range of phase angles (53°  $\pm$ 1°), variations in incidence and emission angles do occur. A correlation between  $D_1$ and the brightness at 760 nm is observed. Variations in brightness result in large part from differences in incidence and emission angles. Therefore, the average variation of about 10% in  $D_1$  observed in the northern hemisphere represents an upper limit on kilometer-scale spectral variations due to surface texture and composition.

Color variations on Eros are more subtle than those documented by Galileo on S asteroids 951 Gaspra and 243 Ida (30). On Eros, the magnitude of the  $D_1$  variations ( $\leq$ 10%) is no more than half of that observed on Gaspra or Ida. In addition, on Gaspra and Ida, but not Eros, such variations are

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accompanied by variations in visible-wavelength color. Thus, in terms of color and spectral variations, the surface of Eros is much more homogeneous than are those of Gaspra or Ida.

NIS spectral and photometric observations. During the low-phase flyby (LPF) on 13 and 14 February, NIS obtained more than 5600 reflectance spectra of Eros covering the wavelength range 800 to 2300 nm. The phase angle varied from about 50° to about 1° at the end of the flyby; the spatial resolution ranged from 12 km per spectrum to just over 2.5 km per spectrum at a closest approach distance of ~200 km.

Natural surfaces exhibit variations in

brightness and lesser variations in color as a function of viewing geometry (38). One common behavior is a marked reddening of spectra with increasing phase angle, an effect even noted in disk-averaged telescopic observations of asteroids (39, 40). We define the radiance factor to be I/F, where I is the measured radiance from Eros and  $\pi F$  is the incident solar radiance. The data cover latitudes between the north pole and 30°N and longitudes between 30°W and 150°E. As expected, I/F increases slowly from large phase angles down to about 10° and then surges more steeply near opposition from 10° to 1° (Fig. 14A). The average phase coefficient (40) between 30° and 10°

phase angle is 0.018 mag per degree and increases to 0.044 mag per degree between 10° and 1°. These results are consistent with the range of phase coefficients determined for natural particulate surfaces from laboratory studies (40). Phase curves at 950 and 2300 nm obtained by NIS (Fig. 14) compare well with a predicted phase curve for Eros at 550 nm (41). A systematic reddening in the phase curve with wavelength is evident, especially in the 2300/ 950-nm reflectance ratio (Fig. 14B). Eros appears redder (more reflective at longer wavelength) at higher phase angles. The observed phase reddening is consistent with previous laboratory studies and



**Fig. 13. (A)** Disk-averaged MSI spectra of Eros compared with groundbased observations. The approach observations of the northern hemisphere (black line) were acquired at phase angles of 49° to 55° and flyby observations of the southern hemisphere (blue and red lines) at phase angles of 82° to 112°. The blue curve represents spectra with the deepest Band I observed; the red curve represents those with the shallowest. Shown for comparison are whole-disk telescopic observations of Vilas





lengths (41). Plotted is the radiance factor *I/F*, where *I* is the measured radiance from Eros and  $\pi F$  is the incident normal solar radiance. The gradual divergence of the curves indicates that over this range of phase angles the

color of Eros reddens with increasing phase. The reddening is evident in the plot at bottom. **(B)** Ratio of the reflectance at 2300 nm to that at 930 nm plotted as a function of phase. Shown are data in red and a linear fit (green).



and McFadden (37) obtained at a phase angle of 39° (dots) and of Murchie and Pieters (34) (dashed line). (**B**) Average reflectance spectrum of Eros obtained by NIS during the LPF on 12 to 13 February 2000 (solid line). The spectrum compares well with MSI data at short wavelengths (solid squares) and with whole-disk telescopic spectra (dotted line) from (34) and JHK color measurements (triangles) from (43). Two absorption features are noticeable: Band I at 1000 nm and Band II at about 1900 nm.

Fig. 15. Plot of the Band I position versus the Band II to Band I area ratio for Eros. Such a representation (45) minimizes the effects on spectral shape of variations in surface texture and lighting and viewing geometry (46). Shown is the data point from the average spectrum obtained by NEAR during the LPF, as well as three points (M&P) from telescopic observations by Murchie and Pieters (35), all of which fall within the S(IV) field defined by Gaffey et al. (45). The



dashed line represents an olivine-pyroxene mixing line. Pure olivines plot in rectangle at upper left labeled OL. As more pyroxene is present, the data point would track along the dashed curve toward lower right. The rectangle labeled BA represent assemblages characteristic of basaltic achondrites. See text for details.

whole-disk measurements of asteroids in general (39, 40).

The resulting average spectrum (42) agrees with previous disk-integrated telescopic reflectance spectra from 800 to 2000 nm (34) and with disk-integrated MSI spectra (Fig. 13B). The comparison between NIS and the telescopic average (34) diverges longward of 2000 nm; however, the NIS data are consistent with disk-integrated broadband JHK photometry at 2200 nm (43), which may provide a more accurate measure of the nearinfrared spectral slope than the FT (Fourier transform) spectra used in (37).

The average NIS spectrum exhibits a spectral slope and Band I and Band II absorption features typical of S-type asteroids (44, 45). The Band I minimum occurs at 1000.0  $\pm$ 13.5 nm and has a depth of  $12.8 \pm 0.6\%$ ; the Band II minimum is at 1918  $\pm$  15 nm and has a depth of 11.8  $\pm$  0.5%. Mixing models indicate that the spectrum can be fit by intimate mixtures composed primarily of olivine, orthopyroxene, and an ill-defined "reddening agent." The latter may be Fe-metal, glass, or an effect analogous to space weathering on the lunar surface (46). Band I and Band II depths were observed to decrease by 2 to 3% with decreasing phase angle, especially at phase angles  $<10^{\circ}$ , consistent with the loss of spectral contrast observed at low phase angles in the laboratory (38, 47). Any nonphotometric variations in the band depths, if present, cannot exceed this amplitude.

A common diagnostic way of comparing asteroid, mineral, and meteorite spectra is to plot Band I position against the Band II to Band I area ratio (BAR) (45). This representation (Fig. 15) minimizes variations caused by changes in grain size and viewing geometry and emphasizes systematic spectral dif-

ferences between olivine and pyroxene, thought to be the major silicate components of S-type asteroids. Our average spectrum for the northern hemisphere falls within the olivine-rich end of the subclass S(IV) (45) and overlaps the putative "olivine-rich hemisphere" point of (34), although their Eros surface coverage is not the same as that of the NIS data. Our data show no dependence of BAR on phase angle. The observed variations (about  $\pm$  5%) can be attributed to measurement uncertainties. In the region covered by the LPF data, there is no evidence in the NIS data for the east-west hemispheric difference in olivine and pyroxene content inferred by Murchie and Pieters (34) from composite telescopic spectra.

The MSI color results and NIS spectra are consistent with an ordinary chondrite composition for Eros and definitely show that marked variations in spectral properties are not present on the surface. Results reported from the NEAR XRS experiments (48) suggest a composition similar to L or LL chondrites. If this suggestion is verified, the accurately determined average density of Eros of 2.67 g/cm<sup>3</sup> implies that the large-scale void volume within the asteroid is less than 30%. suggesting that this S-type asteroid is much more coherent mechanically than the rubblepile structure discovered by NEAR for Ctype asteroid Mathilde for which the porosity must exceed 50% (3).

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# The Shape of 433 Eros from the NEAR-Shoemaker Laser Rangefinder

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Measurements from the Near Earth Asteroid Rendezvous (NEAR)–Shoemaker Laser Rangefinder (NLR) indicate that asteroid 433 Eros is a consolidated body with a complex shape dominated by collisions. The offset between the asteroid's center of mass and center of figure indicates a small deviation from a homogeneous internal structure that is most simply explained by variations in mechanical structure. Regional-scale relief and slope distributions show evidence for control of topography by a competent substrate. Impact crater morphology is influenced by both gravity and structural control. Small-scale topography reveals ridges and grooves that may be generated by impact-related fracturing.

The sizes and shapes of asteroids contain information about the thermal, collisional, and dynamical histories of these bodies, many of which are remnants of the materials from which the solar system accreted. Some analyses (1, 2) have proposed that for all but the handful of largest asteroids, shape is controlled by collisions, with only a minor contribution from self-gravitation. However, other analyses (3, 4) have favored the hypothesis (5) that asteroids are rubble piles, i.e., aggregates held together by gravitational attraction rather than material strength. The geometries of impact structures on all but the smallest (100 m to 1 km) asteroids are also thought to be dominated by gravity (6-9). Precise measurements of topography at a range of spatial scales now enable the influences on an asteroid's collisional history to be quantitatively established.

The NEAR-Shoemaker spacecraft is currently in orbit about the near-Earth asteroid 433 Eros and is performing systematic global mapping at varying orbital altitudes. During elliptical and circular orbit phases of the NEAR mission (10, 11), the NLR (12–14) has so far collected  $\sim 8$  million measurements of the range from the spacecraft to the astertra for which the NIS aperture did not fall entirely on the asteroid, thus avoiding spurious instrumental effects. Spectra exhibiting saturation or *I/F* values below a threshold value (10%) were also eliminated.

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oid (Fig. 1) (15). From these data we have constructed a topographic model of Eros (Fig. 2) with a spatial resolution of 960 m and a radial accuracy of  $\sim$ 30 m (16) with respect to the asteroid's center of mass (17).

Eros has a mean radius of  $7311 \pm 10$  m (Table 1) and exhibits excursions in the equatorial plane that range from ~3500 m to over 17,500 m. The maximum chord is 32.697 km (oriented along 3.96°N, 185.47°E to 0.31°S, 18.69°E), consistent with an orbital value of 31.4 km based on imaging (*18*) and with a ground-based estimate of 36 km derived from analysis of radar echo spectra (*19*).

The best-fit ellipsoid (Table 2) fits the observed shape with a root mean square (rms) of 1028 m. Compared with other asteroids and small moons imaged by spacecraft or for which stellar occultation limb profiles are available (20), Eros's deviation of nearly 60% from its ellipsoidal radius represents a poor fit to an ellipsoid. However, at least some of the variance may be a consequence of the high spatial resolution of our topographic model, which accentuates departures from simple shapes. While Eros's shape deviates from an ellipsoid, the asteroid shows no evidence of a dumbbell shape that would suggest a contact binary bound loosely by self-gravitation as observed for some asteroids (21, 22).

Moments derived from the shape model assuming a constant-density interior [Web table 1 (23)] indicate that Eros has a stable rotation. The extent to which a constant-density interior is characteristic of the asteroid can be quantified to first order from the offset between the center of mass (COM) and center of figure (COF), which is indicative of density inhomogeneities within the body. For an object in a mass-centered coordinate system, the COF is equivalent to the COM of an identical object of homogeneous density

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