Radio Science Results During the NEAR-Shoemaker Spacecraft Rendezvous with Eros

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We determined the mass of asteroid 433 Eros, its lower order gravitational harmonics, and rotation state, using ground-based Doppler and range tracking of the Near Earth Asteroid Rendezvous (NEAR)–Shoemaker spacecraft and images of the asteroid's surface landmarks. The mass of Eros is (6.687 ± 0.003) × 10^{18} grams, which, coupled with our volume estimate, implies a bulk density of 2.67 ± 0.03 grams per cubic centimeter. The asteroid appears to have a uniform density distribution. The right ascension and declination of the rotation pole are 11.37 ± 0.05 and 17.22 ± 0.05 degrees, respectively, and at least over the short term, the rotation state of Eros is stable with no measurable free precession of the spin pole. Escape velocities on the surface vary from 3.1 to 17.2 meters per second. The dynamical environment of Eros suggests that it is covered with regolith and that one might expect material transport toward the deepest potential wells in the saddle and 5.5-kilometer crater regions.

Radio science analyses offer one of the few techniques available for probing the internal structure of asteroids. Doppler and range measurements of the orbiting spacecraft, together with optical observations of Eros landmarks and laser altimetry made on board the NEAR spacecraft, can be used to determine the asteroid's mass, gravity field, shape, bulk density, rotation rate, and spin pole motion (*1, 2*). In turn, these quantities can be used to constrain the density distribution and determine the surface escape velocities and gravitational accelerations that are key to understanding the development of a regolith.

A successful spacecraft rendezvous with Eros was achieved when a maneuver of 11.3 m/s on 3 February 2000 and a smaller one (1.9 m/s) 5 days later reduced the relative velocity of the spacecraft with respect to Eros to 10 m/s. Nearly all of this 10 m/s was removed during the orbit insertion maneuver (OIM) on 14 February 2000. At 1533 UT on 14 February 2000, the spacecraft OIM took place, resulting in a 321 km by 366 km orbit about Eros. The series of maneuvers that reduced the spacecraft orbit in stages to a near-circular 50-km orbit is shown in Fig. 1.

The orbit determination process for a spacecraft in orbit about a small asteroid is a challenging one because the gravitational grip of the asteroid is not firm and the orbital velocities are relatively low (about walking speed in the initial high orbit). The process is complicated by the need for simultaneous solutions for all of the parameters to be estimated in the weighted least squares estimation process (*3*). As a result, the orbit determination process must sneak up on the correct global solution by using rather good a priori estimates of solution parameters—estimates derived from a previous orbital solution. Thus, a successful final solution for a set of estimated parameters depends on a number of successful previous solutions. Simultaneous solutions were made for the gravitational constant times the asteroid's mass (GM), the spherical harmonic coefficients of the asteroid's gravity field (*4*), corrections to the ephemerides of Eros and the spacecraft position vectors for each surface landmark, Eros' rotation pole position, the velocity changes for each spacecraft maneuver, and stochastic spacecraft accelerations and those due to radiation pressure. Orbiting a low-mass, irregularly shaped body like Eros presents some unusual circumstances. For example, in the lowest direct orbits, the spacecraft's motion will not be stable below 35 km, and in the higher orbits, the solar radiation pressure on the NEAR spacecraft will cause its orbital focus to be offset from Eros' center of mass. For example, this antisunward offset amounts to 0.9 km in the 200-km circular orbit.

The spacecraft positions were tracked with radiometric data acquired by the Deep Space Network during routine tracking of the spacecraft. The radio frequencies used for the Doppler tracking were X-band uplink (7182 MHz) and downlink (8438 MHz), and ranging measurements were taken during each tracking interval. The data interval for the solution reported here extended from 15 March through 2 May. This interval included the orbit maneuvers on 2, 11, 22, and 30 April as well as a much smaller maneuver on 23 March to spin down the momentum wheels that are used to control the spacecraft's attitude. The observed Doppler shift was averaged over 1-min count times and weighted with a noise of 0.012 Hz. In addition to the Doppler tracking data for the NEAR spacecraft, there were also range data included in the final solutions. These data were weighted with a noise of 500 m, a value that was ~10 times the postfit range residuals.

Estimates of the asteroid's surface-feature locations (landmarks) were used as data in the combined solution to determine certain circumstances of the encounter and the mass and the rotation state of the asteroid (Table 1). These data consist of line and pixel locations of the landmarks in the multispectral imager (MSI) charge-coupled device images. In the orbit solutions, these landmark image data were weighted with a 1-pixel noise value, about the level of postsolution root mean square residuals. The landmark data are particularly powerful in determining the asteroid's pole and spin characteristics and relating the spacecraft's position to that of the asteroid. These landmark observations consist of measured coordinates in the camera's image plane of certain crater images or landmarks on the surface of Eros. The ideal crater for navigation purposes is small and round, with smooth edges, fairly deep (so that it is easily visible at low angles of incidence), and impossible to confuse with its surroundings. About 10% of the ~900 identified craters are usable for navigation. Furthermore, the set of navigation landmarks can change: As NEAR's orbit shrinks, larger craters are replaced from time to time by smaller ones. The craters are also selected with an eye toward uniform distribution over the surface.

Determining the centroid of each crater image is computer assisted. An ellipse is fixed to the points selected. The center of the ellipse becomes the observable, and the size and orientation of the ellipse are saved to provide information on the body-fixed direction of the surface normal at the crater. This process actually locates a point in the plane of the crater rim, not the surface point that lies at the center of the crater. Small camera misalignment corrections are applied to these landmark data before they are used in the orbit determination process (*5*).

In the orbit solutions, three components of a spacecraft stochastic acceleration vector

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were determined at the end of each 1-hour batch of data. These stochastic accelerations were modeled as zero mean with 10^{-12} km/s^2 of noise and a 2-day correlation time. The data in the final solution included the ground-based Doppler and range tracking of the spacecraft and the Eros landmark observations. These data were combined into one orbit determination solution that solved for the estimated parameters by making a weighted least squares fit to the observational data (*6*). The dynamic model used in the orbit determination process incorporates the gravity (including relativistic effects) of the sun, the moon, and all nine planets. The asteroid mass was determined to be $(6.687 \pm 0.003) \times 10^{18}$ g.

To determine the asteroid's bulk density, we used a volume estimate derived from our shape model. This shape model was derived from the NEAR laser range finder (NLR) data. Every 10th NLR measurement (>30,000 points) over the interval from 2 April through 12 May was fit by a 24th degree and order harmonic expansion of the surface, and the resultant shape was verified by comparison with the landmarks used in the spacecraft navigation process. The landmarks were generally within 200 m of the shape model surface. The volume of the Eros shape model was computed by numerical integration to be 2503 ± 25 km^3, a value that is within the error bounds of the estimates provided by the MSI/near-infrared spectrometer (NIS) and NLR teams (*7, 8*). The bulk density is then 2.67 ± 0.03 g/cm^3. The bulk density for Eros is similar to that determined for 243 Ida with the Galileo spacecraft data (*9*), suggesting a similar interior structure and/or composition. Eros and Ida are in so-called S-type spectral classes and may have similar surface compositions. Within the stated uncertainties, the rotation pole position and rotation rate that we determined for Eros (Table 1) are consistent with the estimates based only on the ground-based data (*10*) and also with an independent analysis of the NEAR images by the MSI/NIS team (*7*).

In terms of unnormalized gravity coefficients (*4*), a body's rotation axis is stable if the following condition holds: J_2 (or $-C_{20}$) > $2J_{22}$, where $J_{22}{}^2 = C_{22}{}^2 + S_{22}{}^2$ (J, C, and S are spherical harmonic gravity coefficients). Because $J_2 = 0.1174$ and $2J_{22} = 0.1124$, the rotation axis should be stable. From the strength of the optical landmark tracking data in the orbit determination solution, it appears that the spin pole of Eros exhibits no noticeable wobble larger than 0.1°.

A comparison of the gravity harmonics and the asteroid's shape model also provides insights into the asteroid's interior structure. The values of the second-degree harmonic coefficients depend on the radial distribution of mass with the J_2 ($-C_{20}$) term being dependent on the object's oblateness and the J_{22} term being a measure of the object's equatorial ellipticity. The moments of inertia about the principal axes also provide valuable insights into the asteroid's mass distribution. However, a direct determination for these moments requires that observations be made of the precessing rotation pole (wobble), and if no appreciable wobble exists (as appears to be the case), no direct determination of the moments of inertia is possible. The shape model determined from the imaging and lidar data was numerically integrated to produce the gravity harmonic coefficients, assuming a constant density throughout the shape of Eros. Table 1 lists the harmonic coefficients for both the gravity model and the shape model. A uniform density for Eros is implied by the similarity of the spherical harmonic gravity coefficients (C_{20}, C_{22}, S_{22}, etc.) determined from the spacecraft trajectory data and the same quantities computed from the shape model, assuming a constant density. For each order of the gravity coefficients in Table 1, we can define the correlation between the true gravity model and the gravity model determined from the shape model, assuming a uniform density. This correlation is the dot product of the two vectors of gravity coefficients in each order divided by the product of their norms. For orders 2, 3, and 4, these correlations are then 0.99997, 0.99933, and 0.99966, respectively, suggesting that the two gravity fields in Table 1 are similar and hence the asteroid's density is uniform throughout. Because the center of mass position is determined from the gravity field and then used for the coordinate system center for the shape model gravity field, the values of harmonic coefficients C_{11}, S_{11}, and C_{10}, determined from the shape model, denote the offset of the shape model origin from Eros' true center of mass. Multiplying each of these coefficients by the reference radius (16 km) and the normalization factor ($3^{0.5}$) gives offsets of 5, 6, and 17 m for the x, y, and z axes, respectively. These rather small values for the offsets again suggest that Eros' mass distribution does not differ substantially from a uniform density distribution. The spacecraft tracking data are more sensitive to the constantly changing asteroid perturbations in the x and y directions and less sensitive to the perturbations in the z (spin pole) direction. Hence, the uncertainty in the center of mass in the z direction is larger than that in the other two directions. The z axis is aligned with the spin pole and is a principal axis. The x axis is defined by a crater location that is some 9° (half the arc tangent of S_{22}/C_{22}) west

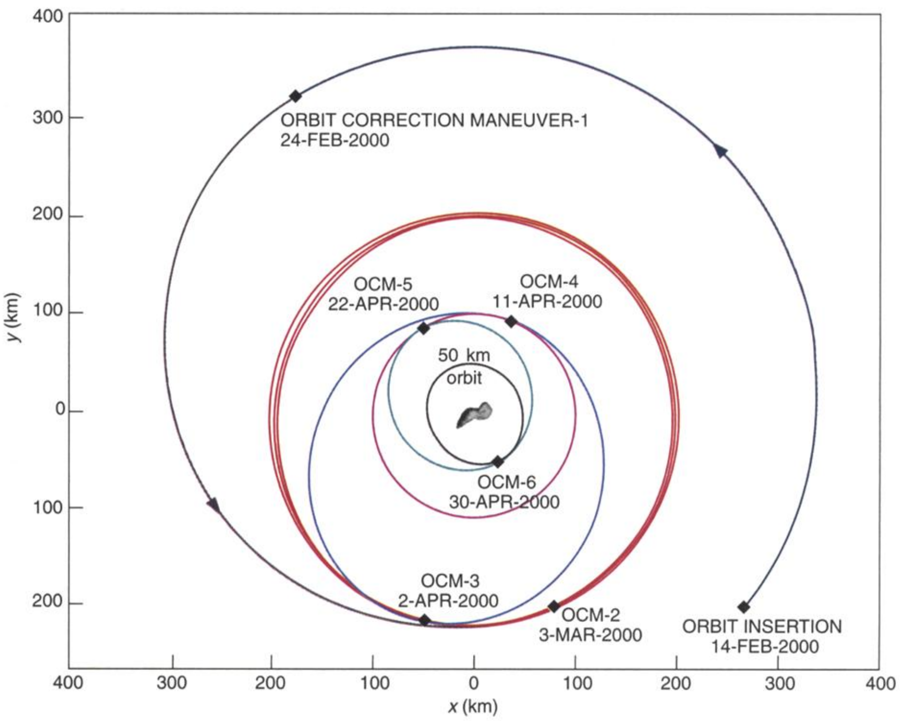

Fig. 1. The orbits of the NEAR-Shoemaker spacecraft about the asteroid Eros. This schematic illustration, as viewed from the sun, shows the NEAR-Shoemaker spacecraft orbits about Eros subsequent to the OIM. After 10 days in a 321 km by 366 km orbit about Eros, the first orbit correction maneuver on 24 February reduced the orbit about Eros to 204 km by 363 km, and another maneuver on 3 March reduced the orbital size further to 204 km by 206 km. A maneuver on 2 April reduced the orbit to 210 km by 101 km, and another on 11 April circularized the orbit at ~100 km. Maneuvers on 22 and 30 April lowered the orbit farther to a near-circular 50-km orbit. By the end of April 2000, the spacecraft was in a 50-km, circular, near-polar orbit, and by mid-July 2000, the spacecraft was down to a 35-km, near-circular, polar orbit.

of the principal axis in the x direction.

Assuming a constant density for the asteroid, the polyhedron shape model of Eros can be used to compute the gravity field at the surface of the asteroid (*11*). Spherical harmonic expansions are no longer valid in this regime and diverge because of the large ellipticity of the asteroid's shape. With the constant density assumption in conjunction with the measured shape model, rotation pole, and rotation rate, a number of quantities of interest for the dynamical characterization of the asteroid can be computed (*12*). Taking rotational effects into account, the slope of the asteroid (the angle between a plumb line and the local surface normal) has an average value of 11°, with only 5% of the surface area having a slope greater than 25°, indicating a relaxed surface with little surface material movement. Surface normal accelerations on Eros vary from a minimum of 2.1 mm/s^2 to a maximum of 5.5 mm/s^2, and surface tangential accelerations range up to 3.4 mm/s^2. The speed sufficient to launch a surface particle directly onto an escape trajectory from Eros (when launched from the surface in the local normal direction) varies by a factor of 5 over the asteroid, from 3.1 to 17.2 m/s. This wide range in escape speeds is due to variations in Eros' gravity and shape coupled with centripetal accelerations due to the asteroid's rotation.

The Roche lobe of Eros is also computed with the measured models (*13*), in this case defined with respect to rotational forces rather than to tidal forces (*14*). The Roche lobe is an iso-energy surface that surrounds Eros and separates it from the rest of the solar system. If a particle close to Eros has less than this energy, then it is impossible for it to "escape" from the asteroid. However, if a particle on the surface is given sufficient speed to increase its energy to the value of the Roche lobe (usually considerably less than escape speed as defined above), it becomes energetically possible for the particle to escape from Eros. A particle that is above the Roche lobe will not fly off the surface, because the local acceleration is still attractive in general, but would be more subject to travel downhill to lower energy positions. For the current Eros model, the entire asteroid surface lies within the Roche lobe, although the distance between the asteroid surface and the lobe is relatively small. The necessary speed for a surface particle to reach the Roche lobe energy ranges from 0.4 to 4.8 m/s over the surface, whereas the distance of Eros' surface from the Roche lobe ranges from 0.02 to 2.6 km, with 65% of the surface lying within 1 km of the Roche lobe. The conformity between the surfaces extends over the entire three-dimensional shape. Because it lies completely within its Roche lobe, the Eros surface is energetically bound. These surfaces are in such close proximity that the Roche lobe has an influence on the distribution of material on the asteroid's surface. In conjunction with the shallowness of the computed slopes over the Eros surface, these results are consistent with a regolith-covered surface. Moreover, the 5.5-km crater and the saddle region are the locations deepest within the asteroid's potential well, and because both locations are surrounded by relatively steep slopes, one might expect regolith transport to these regions.

Table 1. Solution set for the properties of asteroid 433 Eros based on NEAR-Shoemaker spacecraft data. RA, right ascension; DEC, declination. The harmonic coefficients used to characterize the Eros gravity model are normalized, and the radius of the reference sphere is 16 km. The C_{10}, C_{11}, and S_{11} terms are zero in the true gravity model because the coordinate origin for this model is at the center of gravity. Because the z axis has been taken as the spin axis, C_{21} and S_{21} are also equal to zero. All uncertainties (in parentheses) are 1σ values.

Property	Value
GM	$(4.463 \pm 0.001) \times 10^{-4}$ km^3/s^2
M	$(6.687 \pm 0.003) \times 10^{18}$ g
Volume	2503 ± 25 km^3
Bulk density	(2.67 ± 0.03) g/cm^3
Range of surface normal gravitational accelerations	2.1 to 5.5 mm/s^2
Range of escape speeds	3.1 to 17.2 m/s
Rotation rate	1639.38816 ± 0.0005 degrees/day
Rotation period	5.27026 hours
Rotation pole position (J2000)	
RA	11.37 (±0.05) degrees
DEC	17.22 (±0.05) degrees

Normalized spherical harmonic coefficients	True gravity model	Constant density shape model
C_{10}	0	0.000630
C_{11}	0	−0.000202
S_{11}	0	−0.000211
C_{20}	−0.052484 (0.000032)	−0.052056
C_{21}	0	0.000317
S_{21}	0	−0.000101
C_{22}	0.082533 (0.000046)	0.082671
S_{22}	−0.027739 (0.000053)	−0.027107
C_{30}	−0.001159 (0.000094)	−0.001701
C_{31}	0.004232 (0.000045)	0.004053
S_{31}	0.003348 (0.000048)	0.003369
C_{32}	0.001834 (0.000101)	0.002004
S_{32}	−0.000689 (0.000108)	−0.000810
C_{33}	−0.010308 (0.000153)	−0.010435
S_{33}	−0.012218 (0.000149)	−0.012145
C_{40}	0.012509 (0.000299)	0.012762
C_{41}	−0.000105 (0.000077)	−0.000258
S_{41}	−0.000050 (0.000076)	0.000198
C_{42}	−0.017488 (0.000249)	−0.017288
S_{42}	0.004872 (0.000243)	0.004389
C_{43}	0.000056 (0.000387)	−0.000223
S_{43}	−0.000332 (0.000376)	−0.000273
C_{44}	0.017534 (0.000486)	0.017571
S_{44}	−0.008993 (0.000490)	−0.008667

References and Notes

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5. Traditional optical navigation requires images of reference stars to be in the same picture as images of the target body. However, star images never appear in pictures of Eros' surface, partly because the asteroid often fills the field of view, partly because the camera is tracking the asteroid so that the stars would be trailed, but mostly because the surface brightness of Eros is so great that the stars would be too dim to register. We therefore obtain the inertial attitude of the camera indirectly, from the telemetered spacecraft attitude as obtained by the onboard star tracker. However, the star tracker and the camera are not adjacent on the spacecraft, and their relative orientation depends on the thermal characteristics of the spacecraft. We therefore take daily pictures of a star field, compare the telemetered attitude to the camera's actual attitude as determined from the stars, and apply the resulting small misalignment to all images taken on that day. Pixel-level changes in the misalignment are quite common and are probably the limiting error source for the optical landmark data.
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15. Much of the work reported herein on the shape, rotation state, and gravity model for Eros was undertaken by J.K.M., using his specially designed software for small-body orbit determination. We thank the NEAR teams for Mission Design, Mission Operations, and the Spacecraft at the Johns Hopkins University's Applied Physics Laboratory and the Navigation Team at Caltech's Jet Propulsion Laboratory for their outstanding 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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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 ± 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 multispectral 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 ≥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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