Estimating the Mass of Asteroid 433 Eros During the NEAR Spacecraft Flyby

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The Near Earth Asteroid Rendezvous (NEAR) spacecraft flew within 3830 kilometers of asteroid 433 Eros on 23 December 1998. The gravitational perturbation on NEAR was evident in the spacecraft tracking data. Ground-based Doppler and range tracking of the spacecraft as well as spacecraft images of the asteroid's center of figure and surface features were used to determine the mass and rotation pole of Eros. The mass of Eros is $(7.2 \pm 1.8) \times 10^{18}$ grams and, coupled with a volume estimate provided by the NEAR imaging team, this mass suggests a bulk density of 2.5 ± 0.8 grams per cubic centimeter. The rotation pole position is 15.6 ($\pm$3.7) degrees in right ascension and 16.4 ($\pm$1.8) degrees in declination, which is consistent with ground-based and NEAR imaging team observations.

Asteroid 433 Eros is second only to 1036 Ganymede as the largest near-Earth asteroid, and its orbital characteristics make it an accessible target for a spacecraft rendezvous mission. Its general spectral classification is a so-called S-type, the most common type in the inner belt of asteroids between Mars and Jupiter. S-type asteroids may be the parent bodies of the ordinary chondrites, the most common type of meteorite (*1*). To constrain the processes by which the asteroids in the inner belt formed, it is important to understand the bulk densities of various asteroid types. By comparing the bulk density of a parent asteroid with the corresponding density of its most likely meteorite analog, a porosity estimate can be made for the asteroid. Bulk density measurements require knowledge of the object's mass and volume; masses and volumes determined from spacecraft observations exist only for asteroids 243 Ida (*2*), 253 Mathilde (*3, 4*), and now Eros.

NEAR is currently scheduled for an Eros rendezvous in mid-February 2000 (*5*); an aborted main engine firing on 20 December 1998 delayed the planned rendezvous with Eros originally scheduled for 10 January 1999 (Fig. 1). NEAR flew by Eros on 23 December 1998 at a close approach distance of 3827 km at a relative velocity of about 965 m/s. Although the main engine burn was aborted on 20 December 1998, there were unscheduled attitude control jet firings that changed the velocity of the spacecraft. As a result, our efforts to determine the mass of Eros became more difficult because these firings increased the spacecraft close approach distance by more than three times the distance that would have been realized if no thrusting had occurred. Even so, the spacecraft tracking data showed evidence for a slight gravitational perturbation from Eros.

Spacecraft flybys of asteroids involve two phases of navigation whereby the heliocentric positions and velocities (called state vectors) of the spacecraft and asteroid are determined separately from ground-based data. To determine the relative circumstances of the spacecraft and asteroid encounter, the orbit determination solutions for the spacecraft were combined with the ground-based pre-encounter Eros ephemeris and with the optical navigation frames taken by NEAR during the period leading up to the Eros flyby.

Many observations of Eros have been taken over a long time interval when repeated close Earth approaches occurred (*6*). Although Eros was discovered in August 1898, prediscovery positions of Eros were subsequently identified in images for the 1893 opposition. The optical data set, used to define the pre-encounter orbit and ephemeris for Eros, extended from 29 October 1893 through 27 April 1998 and included 3244 sets of observations (that is, observation time, right ascension, and declination). In addition three radar Doppler observations taken during Earth approaches in January 1975 and December 1982 were included in the solution. Even though the last optical observations of Eros included in the final pre-encounter orbit were in April 1998, the pre-encounter analysis of the spacecraft tracking data and spacecraft optical images suggest that the a priori Eros ephemeris accuracy, based on ground-based observations alone, was about 20 km or better.

The spacecraft orbit before the Eros flyby was determined with radiometric data acquired by the Deep Space Network during routine tracking of the spacecraft. The radiofrequencies used for the Doppler tracking were X-band uplink (7182 MHz) and downlink (8438 MHz), and ranging measurements were taken during each tracking interval. For the purposes of mass determination of Eros, the data arc for the spacecraft Doppler data extended from 25 November 1998 through 12 January 1999. This time interval included the aborted rendezvous maneuver on 20 December 1998 and the so-called deep space maneuver on 3 January 1999, which changed the velocity of the NEAR by about 16 and 932 m/s, respectively. Near the time of encounter, tracking data were received from the 34-m high-efficiency antennas at Goldstone, California (station 15), and near Madrid, Spain (station 65). The Doppler noise was compressed to a 10-min count time and weighted with a noise of 0.006 Hz. Because the spacecraft turned its antenna away from the Earth,

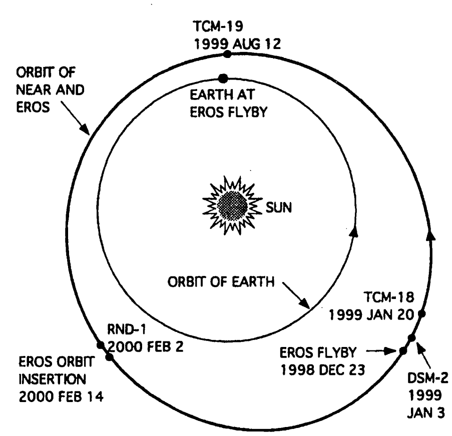

Fig. 1. The orbits of Eros and the NEAR spacecraft lie on top of each other in this heliocentric, ecliptic plane projection. The scheduled main engine firing on 20 December 1998 was aborted so the rendezvous with Eros did not take place as planned in mid-January 1999. However, attitude control thrusters did impart a change in the spacecraft velocity of about 16 m/s. The spacecraft flew past Eros on 23 December 1998 at a relative velocity of 965 m/s. Subsequently, deep space maneuver number 2 (DSM-2; 932 m/s) and trajectory course modification number 18 (TCM-18; 14 m/s.) were executed to alter the spacecraft's velocity. Additional small course modifications on 12 August 1999 (TCM-19; 21 m/s) and two in February 2000 (total = 20 m/s) will match the orbit of the NEAR spacecraft with that of Eros and effect an Eros rendezvous on 14 February 2000.

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there were data losses near closest approach so some of these data were compressed to 5- and 1-min counts. In addition to the anomalous thrusting events, a 27-hour data dropout began on 20 December 1998 at 22:25 UTC. Three days later, there was also a 2-hour tracking data dropout near closest approach. It was unfortunate that these data were not available for determining the mass of Eros because the effect of Eros's mass perturbation on NEAR reached a maximum at closest approach. 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 by using a noise of 100 m, a value consistent with the post-fit range residuals.

Before the distant optical navigation frames and the close-in landmark frames taken by the NEAR multispectral imager (MSI), the spacecraft and Eros orbit solutions were uncorrelated with each other and there was a possibility for large systematic errors in the flyby solution. Therefore, the spacecraft images of the asteroid were critical observations for the terminal navigation process (*7*). As the spacecraft approached the asteroid, the spacecraft optical navigation images (hereafter called OpNavs) of Eros against a star background were used to improve the relative positions of the two objects. In the 3 months before the NEAR encounter, several OpNavs were derived from hundreds of far-encounter images. These OpNavs, whose root mean square (rms) residuals were 0.3 pixel (30 to 50 μrad), were used to improve the relative positions of the spacecraft and Eros. The techniques for obtaining these OpNav NEAR images have been described (*3*). These OpNavs were processed with the Jet Propulsion Laboratory's Optical Navigation Program (*8*).

Estimates of the asteroid's surface feature locations (landmarks) were used as data in the combined solution to determine certain circumstances of the encounter, the mass, and the rotation state of the asteroid (Table 1). Most of the landmark tracking images were taken within 3 hours before the closest approach when the lighting was optimal. A total of 12 navigation landmarks were identified in a set of 15 NEAR OpNavs. These data consist of line and pixel locations of the landmarks in the MSI images. On average, about half the landmarks are on each image, and the landmark data set therefore consists of about 90 line and pixel pairs. These landmark image data were weighted by using a 0.5-pixel noise value, about the level of the post-solution rms residuals. In each solution, the three components of a stochastic acceleration vector were determined at the end of each 6-hour batch of data. These stochastic accelerations were assumed to have a zero mean with 2.0×10^{-12} km/s^2 of white noise and a 2-day correlation time. The data in the final solution included the ground-based Doppler and range tracking of the spacecraft, the spacecraft OpNavs, and Eros landmark observations. A sophisticated software set, specifically designed and developed for this task by J. K. Miller, was used to combine all these data into one orbit determination solution that solves for the solution parameters by making a weighted least-squares fit to the observational data (*9*). The final solution yielded the mass of Eros, ephemeris corrections for the spacecraft and Eros, landmark locations, the Eros rotation pole position, the magnitude and the direction of the spacecraft velocity perturbations on 20 December 1998 and 3 January 1999, stochastic parameters, and the solar radiation pressure acting on the spacecraft. It became apparent that a successful solution for the mass of Eros required a simultaneous solution for all these parameters. 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 solar radiation pressure acting on the spacecraft was modeled by incorporating all known spacecraft attitude changes and recomputing the total radiation pressure acting on a model of the NEAR spacecraft.

Eros's gravitational perturbation on the NEAR spacecraft during the flyby produced a shift in the spacecraft's Doppler data of about 0.006 Hz (0.1 mm/s). By including the value of Eros's GM (gravitational constant × mass of Eros) as one of the solution parameters in the combined orbit determination process, the observational data imply a GM of 4.8×10^{-4} km^3/s^2 with an uncertainty of 25%. With an equivalent uncertainty, the corresponding mass is then 7.2×10^{18} g. The percentage uncertainty on this determination is far larger than for the Mathilde mass determination (*3*) because the Doppler signal resulting from the Eros mass perturbation on NEAR was not significantly above the noise on the Doppler data. A meaningful Eros mass determination would not have been possible without the availability of the on-board imaging data. The deflection angle of the NEAR trajectory as a result of Eros's gravitational interaction was about 0.06 arc sec, and the total heliocentric change in velocity was about 0.15 mm/s. In conjunction with the volume estimate determined by the NEAR MSI team (*7*), the estimated bulk density of Eros is 2.5 ± 0.8 g/cm^3. The bulk density for Eros is similar to that determined for 243 Ida with the Galileo spacecraft data (*2*), which suggests a similar interior structure or composition. Eros and Ida have so-called S-type spectral classes and may have similar surface compositions (*1*). The most likely meteorite analog for Eros will have to await the elemental composition measurements that will be made while NEAR is in orbit. However, it seems unlikely that Eros has the same high porosity as that suggested for the C-type asteroid Mathilde (>50%), a determination that is based on data from the NEAR flyby on 27 June 1997 (*3, 4*). Within the stated uncertainties, the rotation pole position we determined for Eros is consistent with the estimates based only on the ground-based data (*10*) as well as an independent analysis of the NEAR images by the MSI team (*7*).

Table 1. NEAR spacecraft flyby of asteroid Eros and impact plane targeting coordinates and uncertainties (1σ).

Time of closest approach (Barycentric dynamical time)	23 December 1998, 18:41:23 (±1.2 s)
Closest approach distance to Eros center of mass	3827 ± 2 km
Flyby speed	0.9648 ± 0.0001 km/s
GM	$4.8 \pm 1.2 \times 10^{-4}$ km^3/s^2
Mass (M)	$7.2 \pm 1.8 \times 10^{18}$ g
Bulk density	2.5 ± 0.8 g/cm^3
Rotation pole position (J2000)	
Right ascension	15.6 ± 3.7 deg
Declination	16.4 ± 1.8 deg

References and Notes

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