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

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Abstract

The terminal navigation of the Near-Earth Asteroid Rendezvous (NEAR) spacecraft during its flyby of asteroid 433 Eros on December 23, 1998 involved coordinated efforts to determine the heliocentric orbits of the spacecraft and Eros and then to determine the relative trajectory of the spacecraft with respect to Eros. Although the gravitational perturbation on the NEAR spacecraft from the nearby Eros was not nearly as obvious as during the asteroid Mathilde flyby in June 1997 (1), this perturbation was evident in the spacecraft tracking data. Using ground-based Doppler and range tracking of the spacecraft as well as spacecraft images of the asteroid's center and surface features, the mass and rotation pole of Eros could be determined. The mass value for Eros was determined to be (7.2 +/- 1.8) x 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 g/cm**3. The rotation pole position determined for the asteroid is compatible with ground-based results as well as those determined by the NEAR imaging team.

After a successful main engine firing on January 3, 1999, the NEAR spacecraft is currently scheduled for an Eros rendezvous in mid-February 2000 (2,3). The initial plan was to begin the rendezvous with Eros a year earlier in mid-January 1999. However, as a result of an aborted main engine firing on December 20, 1998, the NEAR spacecraft could not carry out the planned rendezvous with asteroid 433 Eros on January 10, 1999. Instead, the spacecraft flew by the asteroid on December 23, 1998 at a close approach distance of 3827 km at a relative velocity of just under 1 km/s. Although the main engine burn was aborted on December 20, 1998, there were also unscheduled attitude control jet firings which did impart a velocity change to the spacecraft. As a result, our efforts to determine the mass of Eros became more difficult since 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 Doppler-tracking data showed evidence for a slight gravitational perturbation from Eros. Figure 1 displays the motion of the NEAR spacecraft and Eros in a heliocentric coordinate system while Figure 2 displays the spacecraft's motion as it would appear to an observer located on Eros.

The following discussion will outline, in turn, the ground-based efforts to predict the ephemeris positions for asteroid 433 Eros and the NEAR spacecraft, the efforts to predict the relative circumstances of the encounter on December 23, 1998, and finally the solution for the mass and rotation state of Eros itself.

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

In terms of its orbit and ephemeris accuracy, asteroid 433 Eros was a particularly fortunate choice for a spacecraft target body (4). This asteroid has numerous observations taken over a very long data arc during which repeated close Earth approaches occurred. Although discovered in August 1898, pre-discovery positions of Eros were identified for the 1893 opposition. The optical data set, used to define the pre-encounter orbit and ephemeris for Eros, extended from October 29, 1893 through April 27, 1998 and included 3244 sets of observations (observation time, right ascension and declination). In addition there were three radar Doppler observations included in the solution. These radar observations were taken during Earth approaches in January 1975 and December 1982. 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 leading up to the Eros flyby was determined solely with radio metric data acquired by the Deep Space Network (DSN) 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 routinely taken during each tracking pass. For the purposes of the mass determination of Eros, the data arc for the spacecraft Doppler data extended from November 25, 1998 through January 12, 1999, intervals that included the aborted rendezvous maneuver on December 20, 1998 as well as the so-called deep space maneuver on January 3, 1999. The velocity changes upon the NEAR spacecraft as a result of these maneuvers were about 16 m/s and 932 m/s respectively. Near the time of encounter, tracking passes were received from the 34 meter High Efficiency (HEF) antennas at Goldstone, California, (Station 15) and near Madrid, Spain (Station 65). The Doppler noise was compressed to a 10-minute count time and weighted with a noise value of 0.006 Hz. Due to the spacecraft turning, there were data dropouts near closest approach so that some of these data were compressed to 5 minutes and 1 minute counts. In addition to the noted anomalous thrusting events, a 27-hour data dropout began on December 20, 1998. Three days later, there was also a two-hour tracking data dropout near closest approach. Since the most powerful data for determining the mass of Eros would have been taken nearest the closest approach, this latter data dropout compromised the mass determination effort somewhat. 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 using a noise value of 100 meters, a value that was consistent with the post-fit range residuals.

Prior to the distant optical navigation frames and the close-in landmark frames taken by the NEAR Multi-Spectral Imager (MSI), the spacecraft and Eros solutions were uncorrelated with each other and there was a possibility for large systematic errors in the flyby solution. Hence, the spacecraft images of the asteroid were critical observations for the terminal navigation process.

As the spacecraft and asteroid approached one another, spacecraft optical navigation images (hereafter called OpNavs) of the asteroid against the star background were used to improve the relative positions of the two objects. In the few months prior to the NEAR spacecraft encounter, several OpNavs were derived from hundreds of far encounter images. These OpNavs, whose root mean square (rms) residuals were 0.3 pixel (30 – 50 microrad.), were used to improve the relative positions of the spacecraft and Eros. The techniques for obtaining these OpNav NEAR images have been previously described (1). These OpNavs were processed using the Optical Navigation Program (5).

For the first time during an asteroid encounter, estimates of the asteroid's surface feature locations (landmarks) were also used as data in the combined solution to determine certain circumstances of the encounter along with the mass and rotation state of the asteroid. Most of the landmark tracking images were taken a few hours before the closest approach when the lighting was optimal. A total of 12 navigation landmarks were identified in a set of 15 NEAR camera (MSI) optical navigation images. These landmark data consist of line and pixel locations of the landmarks in the MSI images. On the 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 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 six-hour batch of data. These stochastic accelerations were assumed to have a zero mean with 2.0 x 10**-12 km/s**2 of white noise and a two day correlation time. The data included in the final solution included the ground-based Doppler and range tracking of the spacecraft as well as the spacecraft OpNavs and Eros landmark observations. Using a sophisticated software set designed and maintained by one of us (J.K.M.; 6,7), all of these data were combined into one orbit determination solution. Included in the final solution were 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 December 20, 1998 and January 3, 1999, stochastic parameters, and the solar radiation pressure acting upon the spacecraft. In accordance with Miller's insight, it became apparent that a successful solution for the mass of Eros would depend upon a simultaneous solution for all of these so-called "solve-for" variables. The dynamic model used in the orbit determination process incorporates the gravity (including relativistic effects) of the Sun, Moon and all the planets. The solar radiation pressure acting on the spacecraft was modeled by incorporating all known spacecraft attitude changes and re-computing the total radiation pressure acting on a model of the NEAR spacecraft.

Eros' gravitational perturbation upon the NEAR spacecraft during the flyby produced a shift in the spacecraft's Doppler data of about 0.006 Hz (0.1 mm/sec). By including the value of Eros' GM (gravitational constant x mass of Eros) as one of the solution parameters in the combined orbit determination process, the observational data implies a GM of 4.8 x 10**-4 km**3/s**2 with an uncertainty of 25%. The corresponding mass is then 7.2 x 10**18 g. The deflection angle of the NEAR trajectory as a result of Eros' gravitational interaction was about 0.06 arc second, 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 (2), the preliminary estimate for the 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 using the Galileo spacecraft data (8) suggesting a similar interior structure. Both Eros and Ida are S-type spectral classes and may have similar surface compositions (10). Within the stated uncertainties, the rotation pole position determined herein is consistent with both the estimate based only on the ground-based data (9) and also the estimate made from an independent analysis of the NEAR images by the MSI team (3). The preliminary mass, bulk density, and rotation pole position noted herein will be improved dramatically when the NEAR spacecraft makes its rendezvous with Eros in February 2000.

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FIGURES

Figure 1: The orbits or Eros and the NEAR spacecraft lie on top of each other in this heliocentric, ecliptic plane projection. The scheduled main engine firing on Dec. 20, 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/sec. The spacecraft flew past Eros on December 23, 1998, at a relative velocity of 965 m/sec. Subsequently, Deep Space Maneuver number 2 (DSM-2, 932 m/s.) and Trajectory Course Correction Number 18 (TCM-18, 14 m/s.) were successfully executed to alter the spacecraft's velocity. Additional small course corrections on 1999 August 12 (TCM-19, 21 m/sec.) and two in February 2000 (total = 19 m/s.) will match the orbit of the NEAR spacecraft with that of Eros and effect an Eros rendezvous in mid-February 2000 (on Valentine's day -- appropriately enough).

Figure 2: This figure is drawn in a rotating coordinate system and in the orbit plane of Eros so the motion of the NEAR spacecraft is given relative to the fixed position of Eros. See the caption for figure 1 for descriptions of the events shown.

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

Time of closest approach:
23 DEC 1998 18:41:23 (+/- 1.2 sec.) TDB

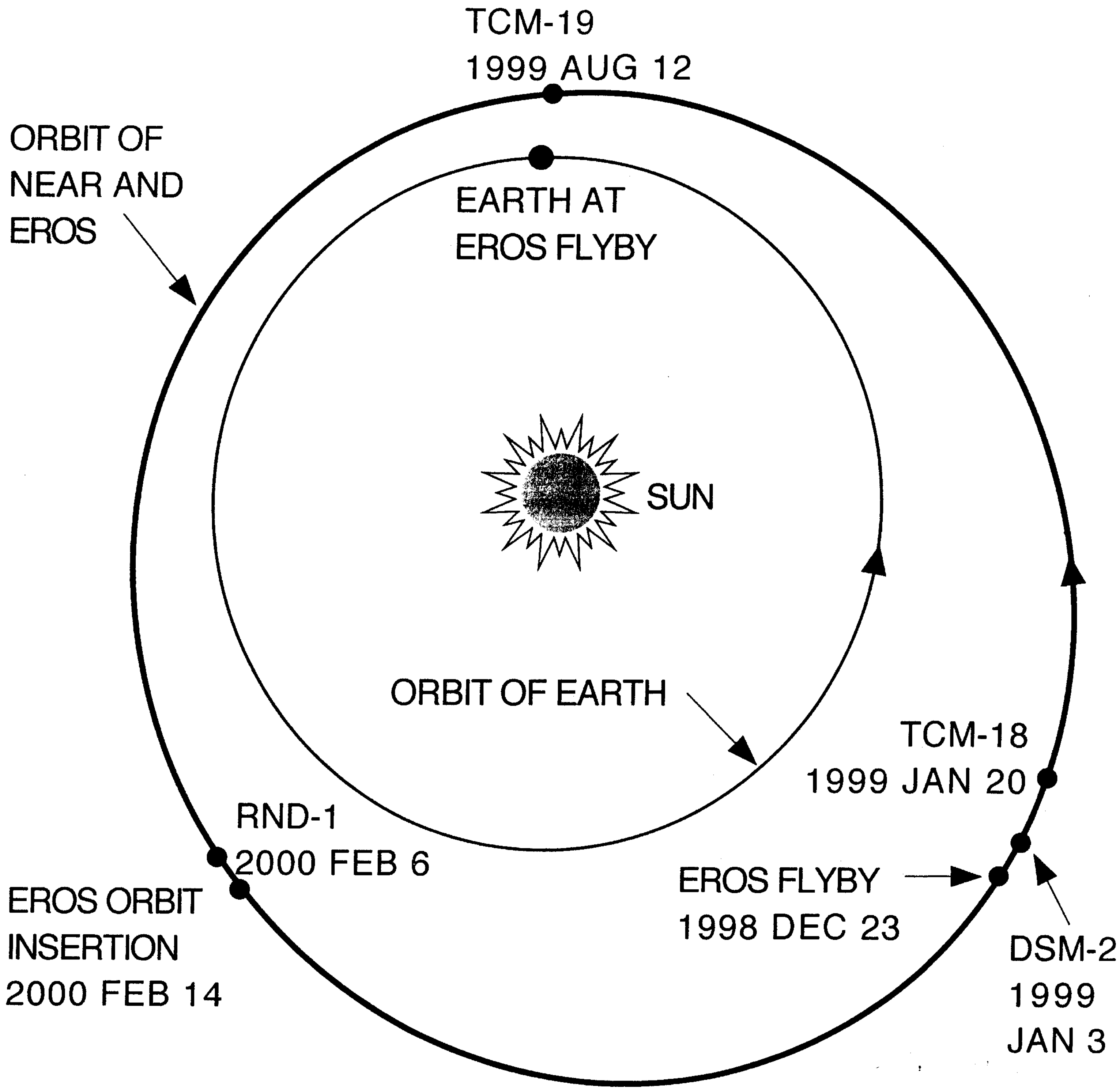
Close approach distance:
3827 (+/- 2) km

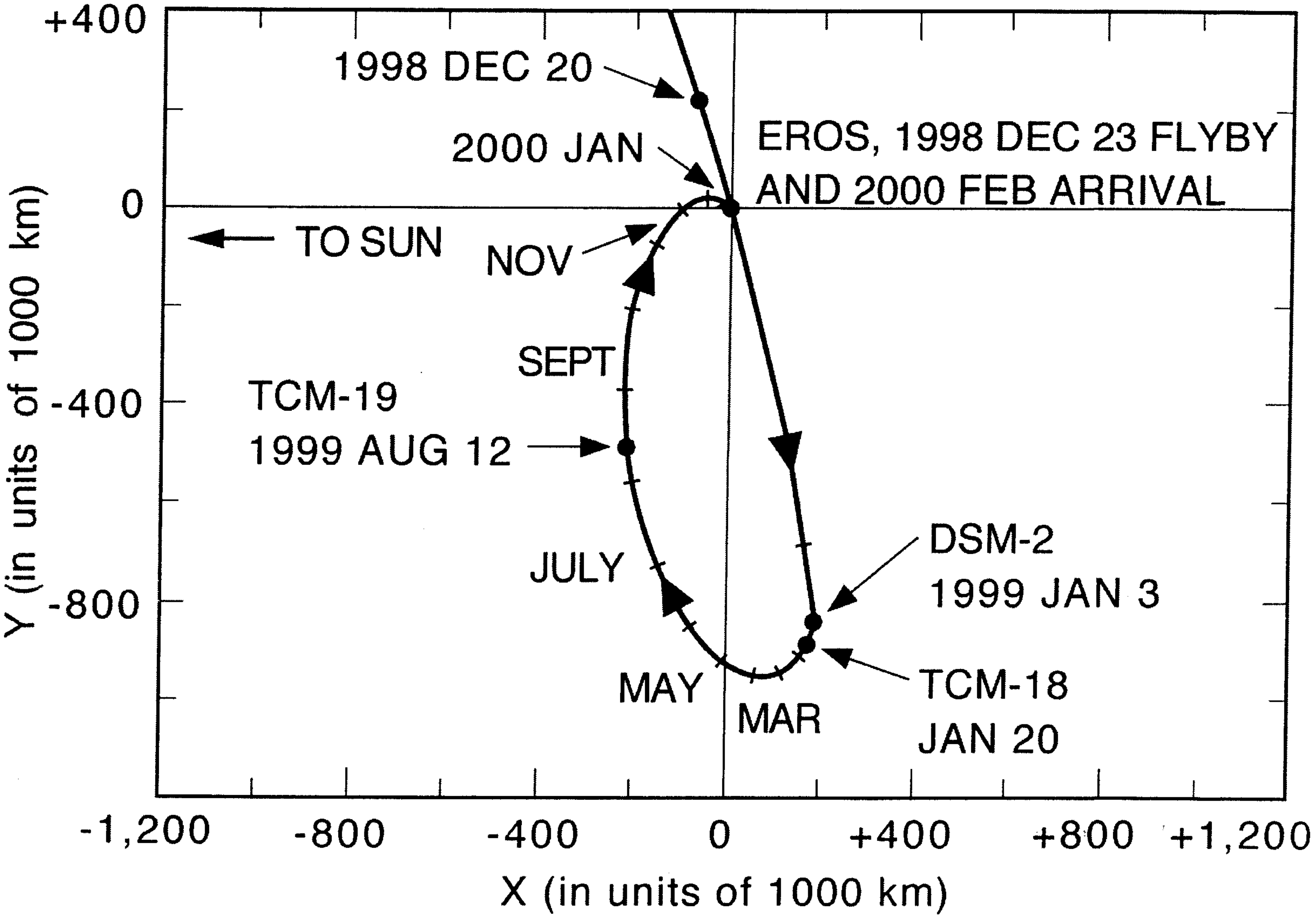
Flyby speed:
0.9648 (+/- 0.0001) km/s

GM (4.8 +/- 1.2) x 10**-4 km**3/sec**2
M = (7.2 +/- 1.8) x 10**18 g

Bulk density = (2.5 +/- 0.8) g/cm**3

Rotation Pole position (J2000)
RA 15.6 (+/- 3.7) deg.
DEC 16.4 (+/- 1.8) deg.


TCM-19
1999 AUG 12
ORBIT OF
NEAR AND
EROS
EARTH AT
EROS FLYBY
SUN
ORBIT OF EARTH
TCM-18
1999 JAN 20
RND-1
2000 FEB 6
EROS ORBIT
INSERTION
2000 FEB 14
EROS FLYBY
1998 DEC 23
DSM-2
1999
JAN 3


+400
0
-400
-800
Y (in units of 1000 km)
-1,200
-800
-400
0
+400
+800
+1,200
X (in units of 1000 km)
1998 DEC 20
2000 JAN
EROS, 1998 DEC 23 FLYBY
AND 2000 FEB ARRIVAL
TO SUN
NOV
SEPT
TCM-19
1999 AUG 12
JULY
MAY
MAR
DSM-2
1999 JAN 3
TCM-18
JAN 20