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Estimating the Mass of Asteroid 253 Mathilde from Tracking Data During the NEAR Flyby

D. K. Yeomans,* J.-P. Barriot, D. W. Dunham, R. W. Farquhar, J. D. Giorgini, C. E. Helfrich, A. S. Konopliv, J. V. McAdams, J. K. Miller, W. M. Owen Jr., D. J. Scheeres,† S. P. Synnott, B. G. Williams

The terminal navigation of the Near Earth Asteroid Rendezvous (NEAR) spacecraft during its close flyby of asteroid 253 Mathilde involved coordinated efforts to determine the heliocentric orbits of the spacecraft and Mathilde and then to determine the relative trajectory of the spacecraft with respect to Mathilde. The gravitational perturbation of Mathilde on the passing spacecraft was apparent in the spacecraft tracking data. As a result of the accurate targeting achieved, these data could be used to determine Mathilde's mass as 1.033 ($\pm$0.044) $\times$ 10^{20} grams. Coupled with a volume estimate provided by the NEAR imaging team, this mass suggests a low bulk density for Mathilde of 1.3 grams per cubic centimeter.

The NEAR spacecraft was designed to rendezvous with asteroid 433 Eros in January 1999 and spend 13 months in close orbit about this near-Earth object. As such, the design and instrumentation of the NEAR spacecraft were optimized for the close orbit of Eros. While refining the trajectory required to effect an Eros rendezvous, the NEAR project identified an opportunity to fly past the unusual and relatively large asteroid 253 Mathilde on 27 June 1997. Although the Galileo spacecraft had made successful flybys of asteroids 951 Gaspra and 243 Ida in 1991 and 1993, both of these asteroids were relatively bright and of the spectral class termed S, whereas Mathilde was thought to be black and of spectral class C (*1*). In addition, the relatively large size of Mathilde and the close flyby distance of 1212 km provided an opportunity to determine Mathilde's mass.

D. K. Yeomans, J. D. Giorgini, C. E. Helfrich, A. S. Konopliv, J. K. Miller, W. M. Owen Jr., D. J. Scheeres, S. P. Synnott, B. G. Williams, Navigation and Flight Mechanics Section, Jet Propulsion Laboratory (JPL), California Institute of Technology, Pasadena, CA 91109, USA.
J.-P. Barriot, Department of Terrestrial and Planetary Geodesy, Centre National d'Etudes Spatiales, Toulouse, France.
D. W. Dunham, R. W. Farquhar, J. V. McAdams, Applied Physics Laboratory, Johns Hopkins University, Laurel, MD 20723, USA.

*To whom correspondence should be addressed. E-mail: donald.k.yeomans@jpl.nasa.gov
†Present address: Department of Aerospace Engineering and Engineering Mechanics, Iowa State University, Ames, IA 50011, USA.

Accurate navigation of the NEAR spacecraft's flyby of Mathilde was required if any of the science objectives were to be realized (*2*). The NEAR spacecraft flew past Mathilde at about 10 km s^{-1}, close to the planned flyby distance of 1200 km. The flyby distance was selected as a trade-off between a distance that was close enough to provide high-resolution (160 m per pixel) images at closest approach, yet far enough so that the angular slew rate would not be too high and there would be enough time for slewing the spacecraft and camera to image the entire area of the sky within which Mathilde was expected. The imaging sequence onboard the NEAR spacecraft could tolerate an error of about 20 s in the time of closest approach before the closest encounter images would be lost. A major source for the NEAR spacecraft's targeting error was the uncertainty in the predicted position of Mathilde (ephemeris uncertainty) at the time of encounter, and this could be improved using approach optical navigation imaging data (hereafter called OpNavs) taken onboard the spacecraft. The final ground-based pre-encounter orbit of Mathilde (JPL reference orbit 49) was based on 610 position observations from 5 December 1885 through 24 June 1997 (*3*).

For fast flybys of target bodies, position errors are often expressed in the so-called "impact plane" of the spacecraft. This impact plane coordinate system is defined by the unitized relative velocity vector between the spacecraft and asteroid at closest approach (**S**), a unit vector (**T**) that is parallel to the Earth mean equator (J2000) and normal to **S**, and by the unit vector $\mathbf{R} = \mathbf{S} \times \mathbf{T}$. The vector **R** points south and **T** points west. Vectors **R** and **T** define the impact plane at closest approach, whereas vector **S** is directed along the relative velocity vector and perpendicular to the impact plane. By using the optical navigation images of the asteroid as seen by the spacecraft (described below), a best estimate of the asteroid's actual position in space at the time of the encounter was determined. The consistency of the results as more and more ground-based pre-encounter observations were included in orbital solutions, as well as the very small differences between the observed and predicted positions of Mathilde (generally less than 0.05 arc sec), allowed an accurate mid-course maneuver to be performed 9 days before the encounter. As a result, a risky maneuver at encounter minus 12 hours was canceled. On the basis of ground-based pre-encounter astrometry alone, the actual Mathilde ephemeris error was only 9 km in the **T** direction and 27 km in the **R** direction. The corresponding error in the direction of the spacecraft's relative velocity was 12.6 km, or, expressed in terms of the time-of-flight error, 1.3 s. (All errors and uncertainties are 1σ values throughout this report.) From ground-based observations alone, the error of Mathilde's ephemeris, at the time of encounter, was less than the size of the asteroid itself.

In addition to providing accurate positional information for Mathilde using Earth-based observations alone, it was necessary to refine these positions with Mathilde images (OpNavs) taken onboard the spacecraft itself. The NEAR flight team took a total of 96 OpNavs of Mathilde against a star background during the last 2 days before the flyby. Because Mathilde was only 40° from the sun, the spacecraft had to be turned so that the solar panels pointed 50° from the sun. The resulting loss of power made these maneuvers risky, and it was decided to take pictures at only six different times, beginning at 41 hours be-

Table 1. NEAR spacecraft flyby of asteroid Mathilde and impact plane targeting coordinates and uncertainties (1σ). Because the OpNavs are taken in the spacecraft's plane-of-sky (impact plane), they can do very little to reduce the uncertainties in the spacecraft-Mathilde direction (**S**).

Time of closest approach	27 June 1997, 12:55:54.5 (± 4.6 s) UT
Close approach distance	1212.2 (± 6.5) km
Flyby speed	9.931564 (± 0.000017) km s^{-1}
Impact plane coordinates	
R (km)	−1208.2
T (km)	−98.2
Joint spacecraft-Mathilde flyby uncertainties (1σ)*	
R (km)	6.5
T (km)	4.2
S (km)	45.8

*Includes pre- and post-encounter optical navigation images.

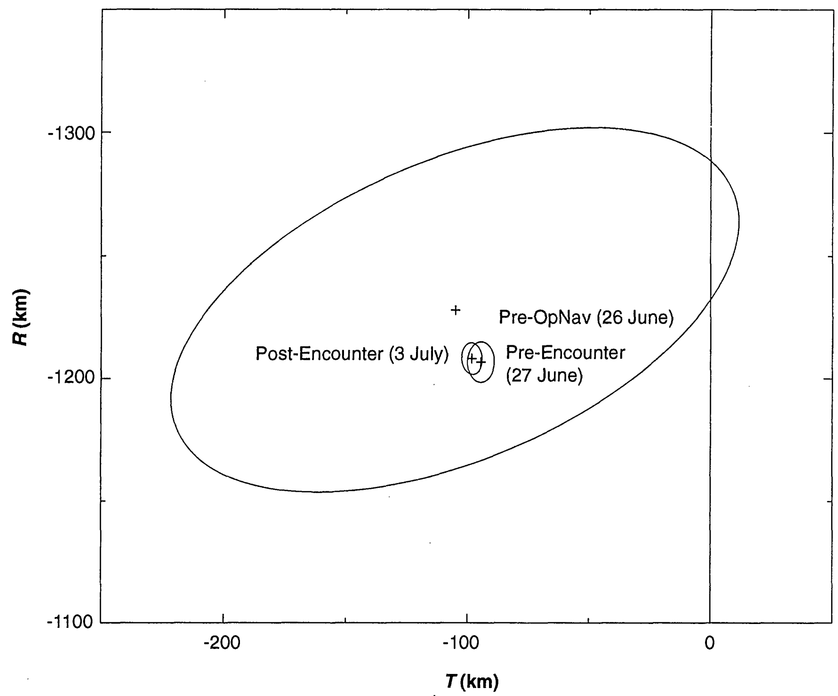

Fig. 1. Mathilde impact plane uncertainties. After the trajectory course maneuver 9 days before the encounter, the nominal aim point for the NEAR spacecraft was the center of the large ellipse, located about 1212 km sunward of Mathilde. This ellipse represents the 1σ targeting uncertainty before the processing of OpNavs. The larger of the two small ellipses represents the Mathilde targeting uncertainty after processing pre-encounter OpNavs 2 to 6; the smallest ellipse represents the post-encounter knowledge of Mathilde after an additional post-encounter science image was used as OpNav 7. In each case, the end date of the tracking data is given in parentheses.

fore closest approach and continuing at about 6-hour intervals until 11 hours before closest approach. The Multi-Spectral Imager (MSI) obtained 16 exposures (each 1 s) through the clear filter at each opportunity. The spacecraft attitude was commanded to drift slightly during the 31 s required for the exposures, so that Mathilde and the stars would move by two pixels between the first and last exposure. The charge-coupled device chip in the MSI is a frame transfer device, and one-quarter of each pixel is not sensitive to light. This slow drift provided protection against Mathilde's image landing on the light-insensitive part of a pixel, and the number of frames protected against data outages and also enabled us to co-add pictures to reduce the background noise.

Observing Mathilde at a solar elongation of only 40° presented two other problems. First, the MSI was not designed to look this close to the sun, and there was a fair amount of stray sunlight in the field, amounting to about 370 DN on the right (sunward) side of the field and increasing to more than 1000 DN on the left side (DN is a data number giving the pixel brightness on a linear scale). Mathilde was centered in the field, where the stray light amounted to 550 ± 6 DN. The increased background noise made detection more difficult and, in effect, raised the minimum detectable star brightness by about one magnitude (*4*). Second, Mathilde presented a thin crescent to the spacecraft. Not only did its high phase angle cut down on its total brightness, it also displaced its center of brightness relative to its center of mass. We were able to treat Mathilde's image as if it were a point source, and then we computed the photocenter offset and applied it to our centroids (*5*).

We found one long-exposure science picture about 12 min after the flyby that contained four usable stars and most of Mathilde. This frame, using a centroid for Mathilde, was added to the data set. The final data set included five co-added frames from OpNavs 2, 3, and 4, seven individual frames from OpNav 5, all 16 frames from OpNav 6, and the lone post-encounter science frame. These centroids were processed using the Optical Navigation Program (*6*), and the residuals and partial derivatives were merged with the radio metric tracking data for orbit and mass determination.

By processing optical navigation frames 2 to 7 in the solutions for the spacecraft and Mathilde orbits, the a priori ephemeris errors resulting from Mathilde's ground-based ephemeris were reduced from about 30 km to less than 10 km in the impact plane of the spacecraft (Table 1). The position error in **S** was not improved because the optical navigation images provided little information about the asteroid's position in the spacecraft-asteroid direction.

The orbit determination solutions for the spacecraft were combined with the ground-based pre-encounter Mathilde ephemeris and with the optical navigation frames taken in the 2 days before the Mathilde flyby. The spacecraft orbit leading up to the Mathilde 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. These radio-based solutions were combined with the ground-based ephemeris of Mathilde to produce solutions that predicted the spacecraft flyby conditions at Mathilde in the impact plane. Before the optical navigation frames (which imaged Mathilde with the NEAR MSI) were taken, the spacecraft and Mathilde solutions were uncorrelated with each other, and the flyby uncertainties in the impact plane were computed by adding the spacecraft and Mathilde uncertainties at the flyby time. Given the lack of correlation between the spacecraft and Mathilde measurements, there was a possibility for large systematic errors in the flyby solution, errors that the OpNavs can detect. Once Mathilde was identified in OpNavs 2 to 6, it became clear that the spacecraft orbit determination errors and the ground-based Mathilde ephemeris were consistent to well within 1σ of the combined orbit determination uncertainties. The OpNavs were then used to correct the relative position of the spacecraft with respect to Mathilde, so as to provide the spacecraft an accurate Mathilde-centered ephemeris to use in pointing its camera during the flyby (Fig. 1). After the flyby, one usable OpNav was identified (OpNav 7) and incorporated into the solution to provide an improved estimate of the flyby conditions and the time of the flyby. Doppler and range measurements of the spacecraft were available continuously from 1 week before the flyby to almost 1 week after the flyby, with a gap of about 1 hour during the flyby when the imaging experiment took place. All these data were combined into one orbit determination solution to estimate the mass of Mathilde and corrections to its ephemeris.

The radio metric data arc used for the final mass solution spanned from 2 June 1997 until 3 July 1997, when a deep-space maneuver occurred. The tracking schedule consisted of two to three 8-hour passes per week leading up to the execution of a trajectory correction maneuver, which occurred on 18 June, after which the tracking was continuous except for 1 hour near closest approach. During each pass, spacecraft Doppler was recorded and range measurements were taken. Tracking passes were received from the 34-m High Efficiency (HEF) antennas at Goldstone, Madrid, and Canberra.

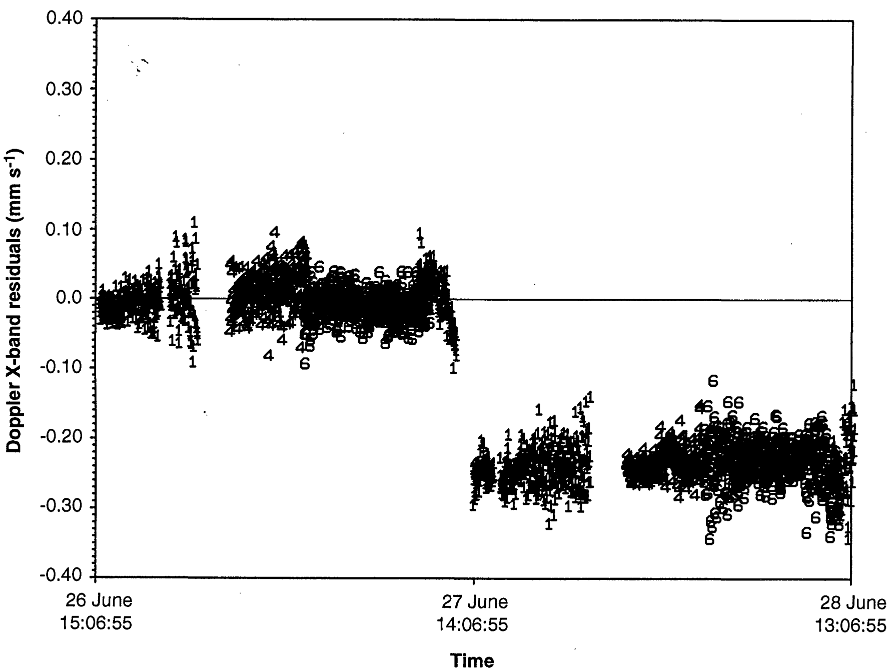

Fig. 2. Doppler tracking residuals during Mathilde flyby. Before the Mathilde close approach on 27 June 1997 at 12:55:55 UT, the differences (residuals) between the observed and predicted spacecraft X-band Doppler measurements were centered on zero. In this example, our predictions assumed a zero mass for Mathilde so that, after the flyby, the residuals shift off zero by an amount (−0.013 Hz = −0.23 mm s^{-1}) equal to that component of Mathilde's velocity perturbation on the NEAR spacecraft that acts along the Earth-spacecraft direction. The residuals marked 1, 4, and 6 represent observations from the DSN's 34-m HEF antennas at Goldstone, California (DSS15), Canberra, Australia (DSS45), and Madrid, Spain (DSS65), respectively.

Table 2. Asteroid mass and density determinations. When noted in the original reference, 1σ uncertainties are given.

Asteroid	Mass (10^{22} g)	Bulk density (g cm^{-3})	Reference
1 Ceres	117 (± 6)	2.3 (±1.1)	*(11)*
	103 (± 6)		*(12)*
	99 (± 4)	2.3	*(13)*
	93 (± 6)		*(14)*
	95 (± 4)		*(15)*
	99 (± 4)		*(16)*
	94 (± 4)		*(9)*
2 Pallas	21 (± 4)	2.6 (±0.6)	*(11)*
	28 (± 4)	3.4	*(13)*
	20 (± 2)		*(9)*
4 Vesta	27 (± 2)	3.3 (±1.5)	*(11)*
	30 (± 6)	3.9	*(13)*
	26 (± 2)		*(9)*
11 Parthenope	0.51 (± 0.02)		*(17)*
243 Ida	0.0042 (± 0.0006)	2.6 (±0.5)	*(18)*
253 Mathilde	0.0103 (± 0.0004)	1.3 (±0.2)	This study

The dynamic model used in the orbit determination process incorporates the gravity (including relativistic effects) of the sun, the moon, and all the planets except Pluto. 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. Many parameters were included in the actual orbit determination solution so that several potential systematic errors were removed, thus allowing the data measurements to be weighted at close to their actual noise values (*7*). Doppler data were weighted at 0.0056 Hz (0.1 mm s^{-1}) and were fit to an accuracy of 0.00149 Hz (0.0265 mm s^{-1}) over the entire arc. Range data were weighted at 1 m and fit to a submeter level, with the station range biases treated as stochastic parameters with a process noise of 0.71 m.

Asteroid mass determinations to better than 30% exist only for 1 Ceres, 2 Pallas, 4 Vesta, 11 Parthenope, 243 Ida, and now 253 Mathilde (Table 2). The values for Ceres, Pallas, Vesta, and Parthenope were computed from their perturbations on another asteroid or Mars, whereas the mass of Ida was estimated using the assumed orbital characteristics of its moon, Dactyl. Mathilde's gravitational perturbation on the NEAR spacecraft during the flyby produced a shift in the spacecraft's Doppler data of 0.0128 Hz (0.23 mm s^{-1}). By including Mathilde's value of GM (gravitational constant × mass of Mathilde) as one of the solution parameters in the combined orbit determination process, the observed Doppler shift implies a GM of 0.00689 ± 0.00030 km^3 s^{-2} and a corresponding mass of 1.033 ± 0.044 × 10^{20} g. The corresponding deflection angle of the NEAR trajectory as a result of Mathilde's gravitational interaction was about 0.11 microradians, and the total heliocentric change in velocity was about 1.12 mm s^{-1}. The Doppler shift attributable to Mathilde's mass perturbation is evident in the spacecraft tracking data, given the level of accuracy seen in the data residuals (Fig. 2).

Before the Mathilde encounter, we had assumed that the effective radius of Mathilde was 30.5 km and its bulk density was 2.5 g cm^{-3}. Thus, the pre-encounter estimate for Mathilde's GM was 0.0198 km^3 s^{-2}. The GM determination above is only one-third of this a priori value. On the basis of the MSI images of Mathilde, the imaging team determined an average radius of 26.5 ± 1.3 km and a nominal volume estimate of 78,000 km^3 with lower and upper limits of 67,000 km^3 and 90,000 km^3, respectively (*8*). The determined mass and volume estimates for Mathilde then suggest a bulk density estimate of 1.3 ± 0.2 g cm^{-3}.

The bulk density for Mathilde is lower than we expected. However, in the 1989 study of the effects of large numbers of asteroids on the orbit of Mars, Standish and Hellings concluded that the average bulk density for the C-class asteroids was 1.7 ± 0.5 g cm^{-3}. As part of an improved planetary ephemeris development effort, Standish found recently that this average value was 1.2 ± 0.1 g cm^{-3} (*9*). Although Standish noted that the given formal uncertainty on this latter value is undoubtedly optimistic, the result is consistent with the present determination of Mathilde's bulk density. If we assume that Mathilde was formed of black chondritic material (*10*) with a density d of about 2.8 g cm^{-3}, Mathilde's bulk density d_M would be 1.3 g cm^{-3}, suggesting that the asteroid's porosity [$p = 1 - (d_M/d)$] is greater than 50%. This level of porosity would suggest that either Mathilde formed from relatively loosely packed fragments or evolved into a "rubble pile" of material as a result of repeated impacts from other asteroids.

REFERENCES AND NOTES

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2. B. G. Williams *et al.*, paper presented at the AAS/AIAA Space Flight Mechanics Meeting, Huntsville, AL, 10 to 12 February 1997.
3. The early Mathilde orbits included only 60 observations over the interval 3 May 1927 to 6 January 1994. In January 1995, E. Goffin made available a data set wherein he had re-reduced many of the existing observations with respect to more modern reference star catalogs and extended the observational interval back to the time of this asteroid's discovery in mid-November 1885. Extensive sets of observations were received from a number of observatories, including McDonald (Texas), Klet (Czech Republic), Modra (Slovakia), Siding Spring (Australia), Oak Ridge (Massachusetts), the Carlsberg Automatic Meridian Circle (Canary Islands), and the U.S. Naval Observatory Flagstaff Station (Arizona). Some of the observations from Flagstaff were reduced with respect to extragalactic radio sources; these observations were given increased weight in the orbit determination process because they were relatively unaffected by the systematic errors present in most reference star catalogs. See R. C. Stone *et al.*, *Astron. J.* **111**, 1721 (1996). Observations taken during the 3 months before the flyby were instrumental in providing an accurate Mathilde ephemeris to the flight project. Beginning on 7 April 1997, observations became available from the observatories of Garradd (Australia), Mauna Kea (Hawaii), and Table Mountain (California). Many of the observations from Table Mountain were reduced with respect to reference stars from the Hipparcos and Tycho star catalogs and were thus upweighted in the orbital solutions because these positions were considered an order of magnitude more accurate than observations reduced with respect to traditional reference star catalogs. Twenty-four of these observations became available covering the dates 21 May, 30 May, 31 May, 17 June, 20 June, 22 June, and 24 June 1997. If these Hipparcos-based positions of Mathilde had not been available before the encounter, and if we had not weighted them strongly in our final orbital solution, the ephemeris errors at encounter would have been at least an order of magnitude larger.
4. Positions for the three bright reference stars in the field were taken from the highly accurate Hipparcos catalog [M. A. C. Perryman, *The Hipparcos Catalogue* (European Space Agency, SP-1200, Noordwijk, Netherlands, 1997)]. Although Hipparcos reference star positions had been made available in advance of publication for improving the orbit of asteroid Ida before the Galileo spacecraft flyby in August 1993 [W. M. Owen Jr. and D. K. Yeomans, *Astron. J.* **107**, 2295 (1994)], the Mathilde encounter marks the first operational use of the Hipparcos catalog by JPL navigation.
5. Our centroiding algorithm modeled the camera's point-spread function as an elliptical Gaussian with 1σ values of 1.7 pixels in the sample direction and 1.0 pixel in the line direction. The DN value in each pixel was modeled by the integrated flux from the point source plus a constant background, with the integration extending over only the light-sensitive part of the pixel. An iterative linearized least-squares procedure then solved for the (x,y) coordinates of the centroid, the brightness of the point source, and the background. This procedure failed at the low signal-to-noise ratio typical of co-added Mathilde images, and we estimated Mathilde's center by eye and lowered the weight appropriately.
6. J. E. Riedel *et al.*, paper presented at the AIAA/AAS Astrodynamics Conference, Portland, OR (20 to 22 August 1990).
7. Besides the spacecraft position and velocity at a 2 June epoch, these parameters include the solved-for magnitude and direction of the maneuver performed on 18 June, nongravitational accelerations, and the Mathilde ephemeris and mass. Error sources treated as considered covariance parameters were the assumed uncertainties in the troposphere and ionosphere refraction and delays, the station location and Earth-moon ephemeris uncertainties, and the optical navigation center-finding and focal length errors. Station range and camera pointing biases were modeled as uncorrelated nondynamic stochastic parameters with a process noise of 0.7 m (range) and 0.01° to 0.03° (camera pointing).
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19. A portion of this research was carried out by the JPL, California Institute of Technology, under contract to NASA. We thank P. W. Chodas, A. B. Chamberlin, M. S. Keesey, E. M. Standish, and R. N. Wimberly for technical assistance and helpful discussions. Important ground-based astrometric observations of Mathilde were provided by observers including M. Buontempo, D. Clowe, A. Galad, G. J. Garradd, E. Goffin, O. Hainaut, A. K. B. Monet, A. Mrkos, R. McNaught, P. J. Shelus, R. Stone, J. Surace, D. Tholen, J. Ticha, A. Whipple, and R. J. Whiteley. M. J. Perryman of the Hipparcos project kindly provided Hipparcos reference star positions in advance of publication. Prepublication estimates of Mathilde's size and volume were kindly provided by the NEAR MSI team, in particular by P. Thomas and the team chief, J. Veverka. A large part of the success of the very difficult encounter with Mathilde was due to the tireless efforts of the NEAR Flight Team (both at Applied Physics Laboratory and JPL). The outstanding leadership of NEAR's systems engineer, A. Santo, deserves special recognition.

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NEAR's Flyby of 253 Mathilde: Images of a C Asteroid

J. Veverka, P. Thomas, A. Harch, B. Clark, J. F. Bell III, B. Carcich, J. Joseph, C. Chapman, W. Merline, M. Robinson, M. Malin, L. A. McFadden, S. Murchie, S. E. Hawkins III, R. Farquhar, N. Izenberg, A. Cheng

On 27 June 1997, the Near Earth Asteroid Rendezvous (NEAR) spacecraft flew within 1212 kilometers of asteroid 253 Mathilde. Mathilde is an irregular, heavily cratered body measuring 66 kilometers by 48 kilometers by 46 kilometers. The asteroid's surface is dark (estimated albedo between 0.035 and 0.050) and similar in color to some CM carbonaceous chondrites. No albedo or color variations were detected. The volume derived from the images and the mass from Doppler tracking of the spacecraft yield a mean density of 1.3 ± 0.2 grams per cubic centimeter, about half that of CM chondrites, indicating a porous interior structure.

The NEAR spacecraft was launched on 17 February 1996 on a 3-year trajectory to the near-Earth asteroid 433 Eros. The spacecraft carries a complement of six science instruments: imager, near-infrared spectrometer, gamma-ray spectrometer, x-ray spectrometer, magnetometer, and laser range finder (*1*); in addition, a radio science investigation analyzes tracking signals from the spacecraft. NEAR will arrive and begin its orbital mission at Eros in early 1999. On its way to Eros, NEAR passed within 1212