Spacecraft Exploration of Asteroids: The 2001 Perspective

Robert Farquhar
Johns Hopkins University

Jun'ichiro Kawaguchi
Institute of Space and Astronautical Science

Christopher T. Russell
University of California at Los Angeles

Gerhard Schwehm
European Space Agency

Joseph Veverka
Cornell University

Donald Yeomans
Jet Propulsion Laboratory

An overview of spacecraft missions to asteroids is presented. Past missions include the *Galileo* flybys of 951 Gaspra and 243 Ida, *NEAR Shoemaker*'s flyby of 253 Mathilde, *Deep Space One*'s flyby of 9969 Braille, and finally *NEAR Shoemaker*'s rendezvous with 433 Eros. Of course, *NEAR Shoemaker*'s yearlong orbital operations at Eros, and subsequent landing on Eros' surface, are the most notable accomplishments thus far, but plans for future asteroid missions are even more ambitious. These plans include a sample-return mission to a near-Earth asteroid, a rendezvous mission to Ceres and Vesta, and flybys of 4979 Otawara and 140 Siwa by the European Space Agency's *Rosetta* spacecraft.

1. INTRODUCTION

In the last ten years, there has been considerable progress in the exploration of asteroids by spacecraft (cf. *Veverka et al.,* 1989). On October 29, 1991, the *Galileo* spacecraft carried out the first every flyby of an asteroid, 951 Gaspra. Less than two years later, on August 28, 1993, *Galileo* encountered a second main-belt asteroid, 243 Ida. Both encounters were accomplished with great technical and scientific success. Especially noteworthy was the discovery of a small natural satellite, Dactyl, in orbit around Ida. Gaspra and Ida are S-type asteroids. The first encounter with a C-type asteroid took place on June 27, 1997, when the *NEAR Shoemaker* spacecraft flew by the main-belt asteroid 253 Mathilde. [On March 14, 2000, the *NEAR* (*Near-Earth Asteroid Rendezvous*) spacecraft was renamed to honor the renowned planetary geologist, Eugene Shoemaker (1928–1997).]

The first spacecraft encounter with a near-Earth asteroid was supposed to occur on August 31, 1994. A Department of Defense spacecraft called "*Clementine*" was scheduled to fly by 1620 Geographos after completing a two-month mission in lunar orbit (*Nozette and Shoemaker,* 1993). Unfortunately, *Clementine* expired shortly before it could be redirected for its intended flyby of Geographos. Nevertheless, the 70-m antenna at Goldstone, California, was used to obtain some spectacular radar images (*Sky & Telescope,* August 1995).

As will be discussed in the next section, the second attempt to investigate a near-Earth asteroid also encountered a few problems. Fortunately, *NEAR Shoemaker* was able to overcome its technical difficulties, and it was eventually inserted into an orbit around the relatively large near-Earth asteroid 433 Eros on February 14, 2000. During its yearlong stay at Eros, *NEAR Shoemaker* obtained a vast quantity of scientific data, including more than 160,000 images.

Future dedicated asteroid missions are likely to rely on advanced spacecraft propulsion to achieve their scientific objectives. Two missions, now in a planning stage, are calling for the use of solar-electric propulsion (SEP). They are Japan's *MUSES-C* sample-return mission to the near-Earth asteroid 1998 SF36, and NASA's *Dawn* mission that is planning to orbit two very large asteroids, Ceres and Vesta. Details of both missions are discussed in this chapter.

2. ASTEROID FLYBYS

Most asteroids to date have been studied during fast flybys at speeds near 10 km/s. Flybys provide a mixed bless-

TABLE 1. Asteroid flybys.

Date	Asteroid	Type	Size (km)	Spacecraft	Closest Approach (km)	Flyby Speed (km/s)	Number of Images	Best Resolution (m/pxl)
October 29, 1991	951 Gaspra	S	18 × 11 × 9	*Galileo*	1600	8	57	54
August 28, 1993	243 Ida	S	60 × 25 × 19	*Galileo*	2391	12.4	96	25
	(Dactyl)	(?)	(1.5)					
June 27, 1997	253 Mathilde	C	66 × 48 × 46	*NEAR*	1212	9.9	330	160
December 23, 1998	433 Eros	S	31 × 13 × 13	*NEAR*	3827	0.9	222	400
July 28, 1999	9969 Braille	?	~2	*Deep Space 1*	28	15.5	1	200
July 11, 2006	4979 Otawara	?	~3	*Rosetta*	2200	10.6	—	—
July 24, 2008	140 Siwa	C	110	*Rosetta*	3500	17.0	—	—

TABLE 2. Physical and orbital parameters of targeted asteroids.

	951 Gaspra	243 Ida	253 Mathilde	9969 Braille	433 Eros	4979 Otawara	140 Siwa
Size (km)	18 × 11 × 9	60 × 25 × 19	66 × 48 × 46	~1 × 2.2	31 × 13 × 13	2.6–4.0	110
Spectral type	S	S	C	V or S	S	V or S	P
Visual albedo	0.23 (0.06)	0.21 (0.03)	0.045 (0.003)		0.25 (0.05)		0.07
Rotation period (h)	7.04	4.633	417	226	5.27	2.7	18.5
Perihelion distance (AU)	1.8	2.7	2.0	1.3	1.1	1.8	2.1
Aphelion distance (AU)	2.6	3.0	3.4	3.4	1.8	2.5	3.3
Orbital period (yr)	3.3	4.8	4.3	3.6	1.8	3.2	4.5
Orbital inclination (degrees)	4.1	1.1	6.7	28.9	10.8	0.9	3.2

ing: They are ideal for obtaining reconnaissance data about asteroids, often on the way to another target, but due to their short duration the information they can capture is limited.

Remote sensing during the flyby is limited by two important factors, distance and the limited duration of the encounter. In terms of distance, past experience suggests that geologic interpretation requires spatial resolution at better than 200 m/pixel. Useful determinations of global characteristics (shape, volume, etc.) require at least 20–50 pixels across the asteroid. The limited duration of flybys leads to two constraints. First, the complement of applicable investigation techniques is limited. To date, X-ray and γ-ray investigations have required integration times that are incompatible with typical flybys. Second, the short duration can limit the completeness of coverage depending on the spin rate and pole orientation of the asteroid. For rapidly rotating Ida (P ~ 4.6 h), *Galileo* was able to see most of the asteroid during its flyby. For slowly rotating Mathilde (P ~ 420 h), *NEAR Shoemaker* saw only a little more than half, leaving the uncertainty in the asteroid's volume 3× larger than in the case of Ida (5% vs. 15%). The December 1998 flyby of Eros by *NEAR Shoemaker* provided an intermediate case. For asteroids in the size range of Gaspra and Mathilde (10–50 km in mean diameter) flybys at no more than 1000–2000 km will produce the best results. Flybys can produce the asteroid mass, which following a reliable estimate of volume, can lead to a determination of the mean density, an important clue to the interior makeup of the asteroid.

One important technical challenge of flybys is the difficulty of pointing accurately at the target during closest approach with high-spatial-resolution cameras that tend to have narrow fields of view. Even following approach, optical navigation downtrack errors remain significant and can amount to several fields of view. Cameras used during past flybys lacked automated tracking capability, a situation that will no doubt continue in the future for flybys carried out as complements to missions with other primary objectives.

To date, five flybys (of six asteroids) have been carried out with varying degrees of success (Table 1). (Physical and orbital parameters of the targeted asteroids are listed in Table 2.) The first was *Galileo*'s flyby of asteroid 951 Gaspra (Fig. 1). *Galileo* showed Gaspra to be a highly irregular, cratered body with principal diameters of 18.2, 10.5, and 8.9 km (average radius = 6.1 ± 0.4 km). Gaspra's irregular shape and the prominence of grooves, linear depressions 100–300 m wide and tens of meters deep, suggested that the asteroid was derived from a larger body by catastrophic collision. Features that appeared to reflect structural grain, including ridges, grooves, and flat surfaces, suggested that Gaspra is a single coherent body.

Analysis of spectral imaging data (0.40–1.10 μm) revealed small but significant color variations over the asteroid's surface. The spectrally most distinct materials on Gaspra were distinguished by a more prominent 1-μm absorption band and tended to be slightly brighter and bluer than average Gaspra. Often such materials are associated

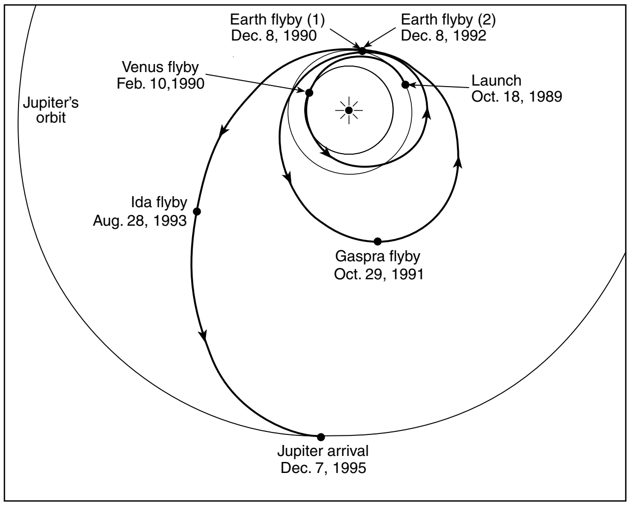

Fig. 1. *Galileo*'s trajectory profile.

with small, fresh-appearing craters along ridges. A strong correlation was found between the infrared/violet color ratio and elevations on Gaspra, a correlation that can be explained in terms of downhill migration of a regolith. No determination of Gaspra's mass was possible.

The biggest surprise during *Galileo*'s second asteroid flyby, that of 243 Ida, was the discovery of a 1.5-km-wide satellite since named Dactyl. From Dactyl's orbit, *Belton et al.* (1996) were able to estimate the mass of Ida. Ida's density (2.6 g/cm^3) turns out to be very similar to that determined for S-type asteroid 433 Eros by *NEAR Shoemaker* (2.67 g/cm^3).

The discovery of Dactyl led to enhanced efforts to search for satellites around Mathilde and Eros. Unfortunately, none were found. However, more than half a dozen satellites of asteroids have been discovered since Dactyl by ground-based observers using optical and radar techniques.

NEAR Shoemaker's encounter with Mathilde is depicted in Fig. 2. This flyby was unusually difficult for a number of reasons. First, the spacecraft approached Mathilde from a phase angle of 140°, which created a severe problem for obtaining optical navigation images. Because *NEAR Shoemaker* was observing Mathilde at a solar elongation angle of only 40°, the asteroid was first detected just 36 h before closest approach as a faint dot almost lost in the Sun's glare. Second, the encounter took place at about 2 AU from the Sun, where the available power from the spacecraft's solar panels was only 25% of its maximum mission level. Furthermore, because the entire spacecraft had to be turned to point the camera at Mathilde, it was necessary to orient the solar panels about 50° away from the optimal solar direction during the encounter, and this reduced the available power by another 36%. Therefore, to conserve power, only one of *NEAR Shoemaker*'s six instruments, the multispectral imager, was on during the encounter. Finally, because *NEAR Shoemaker* did not have a scan platform for the camera, the design of the imaging sequence was more complicated than usual.

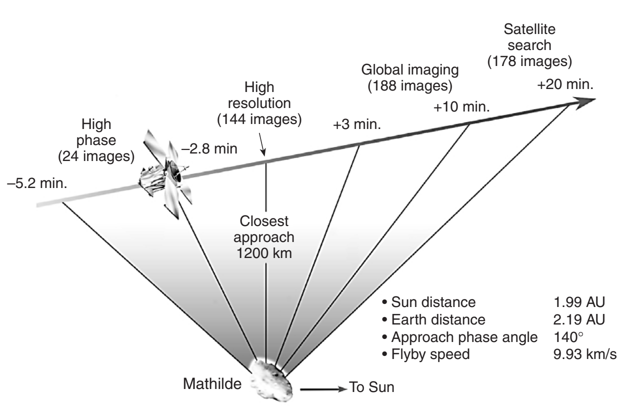

Fig. 2. Mathilde encounter: June 27, 1997.

Nevertheless, in spite of the aforementioned obstacles, the flyby was flawless. As shown in Fig. 2, the imaging sequence began some 5 min before closest approach, when views of a crescent-illuminated Mathilde were obtained at about 500 m/pixel. The highest-resolution data were obtained at closest approach, when the phase angle was close to 90°. The imaging sequence continued for another 20 min as the spacecraft receded from the asteroid. Although *NEAR Shoemaker* took 534 images, about 200 frames were devoted to a search for satellites.

NEAR Shoemaker's images of Mathilde, a classic C-type asteroid, revealed an irregular and heavily cratered body. Within the roughly 50% of the total area imaged by *NEAR Shoemaker*, there are five craters with diameters between 19 and 35 km. The largest and best-imaged crater is 33 km across and may be 5–6 km deep. The asteroid's surface is very dark (albedo between 0.035 and 0.050) and similar in color to some CM carbonaceous chondrites. No albedo or color variations were detected.

Mathilde's mass was determined by accurately tracking *NEAR Shoemaker* before and after the encounter. Except for a short interval during the close approach period, continuous tracking of the spacecraft was performed from one week before to almost one week after the flyby. The tracking data led to a mass estimate for Mathilde of 1.033 (±0.044) × 10^{20} g (*Yeomans et al.,* 1997). This mass estimate coupled with a volume estimate from the imaging team yielded a bulk density for Mathilde of only 1.3 g/cm^3.

Mathilde's low density indicates that it is probably a "rubble pile," whose interior has been pulverized by a long history of collisions. The existence of such underdense objects has been predicted by several studies. Finally, it is also possible that if C-type asteroids consist of very primitive, unprocessed materials, their low density may in some sense be primordial.

NEAR Shoemaker's second asteroid flyby was unplanned. It was the result of a botched rendezvous maneuver on December 20, 1998. *NEAR Shoemaker*'s control center lost contact with the spacecraft about 37 s after the start of the maneuver. Although communications were restored 27 h later, it was not possible to execute another maneuver before *NEAR Shoemaker* would pass Eros on December 23. With less than 24 h to get ready for the Eros flyby, engineers and scientists worked through the night to update *NEAR Shoemaker*'s observing sequence. Due to uncertainties in the asteroid's position relative to the spacecraft, it would be necessary to image a significant area of the sky to be sure of getting pictures of Eros near closest approach. Unfortunately, the aborted rendezvous burn and ensuing attitude maneuvers had pushed the spacecraft far off its intended course. Instead of the originally planned 1000-km miss distance, *NEAR Shoemaker*'s closest approach to Eros was 3827 km. This meant that the smallest detail resolved by *NEAR Shoemaker*'s camera was about 400 m across. Nevertheless, the first close-up encounter with a near-Earth asteroid yielded 222 images of Eros as well as supporting spectral observations (*Veverka et al.,* 1999).

Fortunately, *NEAR Shoemaker* had a forgiving mission design that had planned for adversity. The design included generous fuel margins and a variety of contingency options. More than any other factor, the resilient mission design was responsible for giving *NEAR Shoemaker* another opportunity to rendezvous with Eros. Although the planned rendezvous date of January 10, 1999, was no longer possible, *NEAR Shoemaker*'s mission planners quickly settled on a strategy that would achieve a rendezvous with Eros in mid-February 2000 (*Dunham et al.,* 2000). The new target date was February 14, Valentine's Day.

The fifth spacecraft flyby of an asteroid was scheduled to take place on July 28, 1999, when the technology spacecraft, *Deep Space 1*, would encounter 9969 Braille. Unfortunately, the science return from this encounter was far less than anticipated. Due to a number of mishaps, only one very distant image was obtained about 15 min after closest approach.

As shown in Table 1, the European Space Agency's *Rosetta* spacecraft is planning to fly by two asteroids, 4979 Otawara in 2006 and 140 Siwa in 2008. Very little is known about Otawara, but Siwa could be an interesting target (*Barucci et al.,* 1998). With a diameter around 110 km, Siwa is larger than any asteroid so far examined by spacecraft. Spectral studies indicate that it is a very black, primitive C-type object that has probably been less altered by collisions than its smaller cousins. It would be particularly interesting to compare Siwa and Mathilde.

Finally, it should be mentioned that the *Stardust* project is considering an encounter with 5535 AnneFrank (diameter ~7 km) on November 2, 2002. However, funding for this potential encounter has not been approved, and the phase angle at encounter is not favorable (~150°).

3. *NEAR SHOEMAKER* AT EROS: ORBITAL OPERATIONS AND A SOFT LANDING

On February 14, 2000, a small propulsive maneuver (ΔV ~10 m/s) was used to place the *NEAR Shoemaker* spacecraft into a 321 × 366-km orbit around Eros. *NEAR Shoemaker*'s orbital history during its first 2.5 months at Eros is shown in Fig. 3. A series of small orbit correction maneuvers (OCMs) gradually brought *NEAR Shoemaker* closer to Eros until it reached its nominal mission orbit of roughly 50 × 50 km on April 30. As the spacecraft descended through these early orbits, physical parameters of Eros such as its mass, gravity field, shape, spin state, and rotation pole orientation were determined with increasing precision (*Yeomans et al.,* 2000; *Zuber et al.,* 2000).

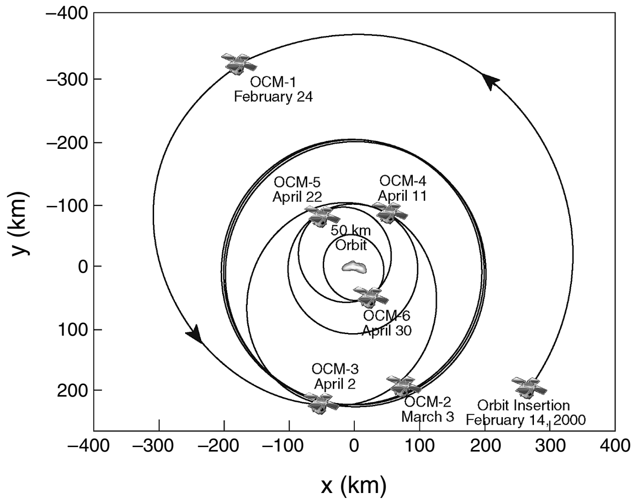

Fig. 3. Early Eros orbit phase (view from Sun).

When *NEAR Shoemaker* arrived at Eros in February 2000, Eros' north pole was oriented toward the Sun and its southern hemisphere was dark. About 4 months later, as Eros traveled along its orbit around the Sun, Eros' rotation axis was perpendicular to the Sun-Eros line. *NEAR Shoemaker*'s orbital geometry at this time (June 2000) is shown in the top half of Fig. 4. The *NEAR Shoemaker* spacecraft is shown in a 50-km circular orbit around Eros as viewed

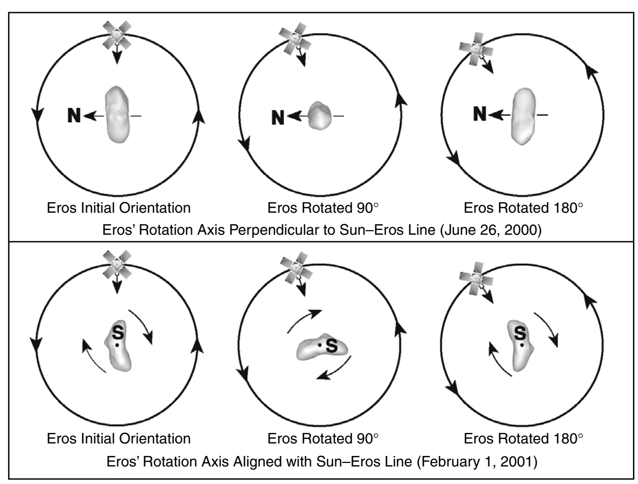

Fig. 4. *NEAR Shoemaker*'s orbital geometry at Eros in June 2000 and February 2001 (view from Sun; orbit size: 50 × 50 km).

by an observer on the Sun. *NEAR Shoemaker*'s orbit and Eros are drawn to scale, but obviously the spacecraft is not. This is a convenient reference frame to show *NEAR Shoemaker*'s orbit because *NEAR Shoemaker*'s orbital plane was controlled so that it was always within 30° of a plane that is normal to the Sun-Eros line. In this configuration, *NEAR Shoemaker*'s fixed solar panels are oriented toward the Sun. The science instruments are pointed at Eros' surface by slowly rolling the spacecraft as it orbits Eros. The orbital geometry in February 2001 is shown in the bottom half of Fig. 4. Here, Eros' south pole is directed at the Sun, and the northern hemisphere is in darkness.

During its initial high-orbit phase, *NEAR Shoemaker* obtained thousands of images of Eros' northern hemisphere at resolutions of about 25 m/pixel (*Veverka et al.,* 2000). Later, when the spacecraft reached its 50 × 50-km orbit, *NEAR Shoemaker*'s camera mapped the surface at scales of 5–10 m. Because *NEAR Shoemaker*'s nominal orbit plane was close to the terminator plane (plane dividing dayside and nightside), most of the images were taken at phase angles near 90°, an ideal geometry for studying the surface because shadows are prominent and reveal details of surface morphology.

In addition to obtaining higher-resolution images, it was necessary to get closer to Eros because the X-ray/γ-ray spectrometer (XGRS) required long observation periods in orbits with radii of 50 km or less. Only the lowest orbits would provide sufficient sensitivity and resolution for the XRGS instrument to measure and map the surface composition of Eros. However, the evolution of low-altitude orbits around Eros is strongly influenced by its irregular gravity field. Orbits exist that are quire unstable, and safe operation in these low-altitude orbits required close coordination between the science, mission design, navigation, and mission operations teams.

During the first low-orbit phase from May 1 to August 26, 2000, *NEAR Shoemaker* spent virtually all its time in a 50 × 50-km orbit. The only exception was a brief 10-day interval in July when it operated in a 35 × 35-km orbit. Because the first operation in 35 × 35-km orbit did not encounter any serious problems, it was decided to go directly to this orbit during the second low-orbit phase (December 2000 to February 2001). This decision was significant because it allowed the XGRS instrument to operate for about 2 months in an orbit that regularly passes by Eros at altitudes under 20 km.

Eros is a small asteroid and hence has only weak gravity. Typically, gravity is 1000× less than on Earth, making it relatively easy for fast-moving ejecta from impacts to escape. While there were previous indications that asteroids even as small as Eros are covered with impact-generated debris, as regolith, some scientists on the *NEAR Shoemaker* project were surprised by how ubiquitous and abundant this impact debris is on the asteroid's surface. Sizeable blocks of ejecta tens of meters across are everywhere and most of the craters are partially filled by finer debris. A global map of all blocks bigger than 30 m was undertaken. This effort

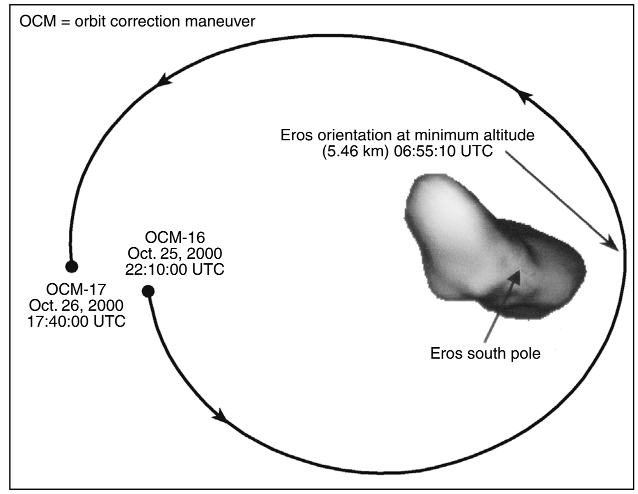

Fig. 5. *NEAR Shoemaker*'s low-altitude flyover of Eros on October 26, 2000 (view from Sun).

produced clear evidence that most of the conspicuous blocks that currently litter the surface of Eros were produced by the impact that formed the most recent large crater on the asteroid: Shoemaker Crater, a scar some 7 km wide. However, the complexity of the regolith raised many questions that could only be answered by getting a closer look at the surface.

The first opportunity for really close images came on October 25, 2000, when *NEAR Shoemaker* swept down to 6.4 km over one of the ends of Eros, allowing the camera to view the surface at a resolution of 1 m/pixel (*Veveka et al.,* 2001a). The minimum altitude for this flyover occurred on October 26 and was roughly 5.5 km (Fig. 5). The success of the October low-altitude flyover led to a second set of low-altitude passes in late January 2001 that ended with a 2.74-km pass on January 28. The January 28 images revealed surface details at resolutions under 0.5 m.

The low-altitude images showed a subdued, gently undulating surface characterized by abundant blocks and conspicuously degraded craters. Many of the degraded craters show evidence of infilling. A novel feature is the occurrence of smooth flat areas (known as "ponds") in the interiors of certain craters. The smoothness of the ponds indicate that there is an efficient process that is able to sort out the finest component of the regolith from the coarser, more blocky portion, and concentrate the fine material into low-lying areas such as crater bottoms.

Even before *NEAR Shoemaker*'s launch, the issue arose as to what should be done with the spacecraft when its primary mission was completed. Should it just be abandoned in its orbit around Eros, or alternatively, could a scientifically useful extended mission be identified?

One adventurous proposal was that *NEAR Shoemaker* should slowly descend to Eros and attempt a landing. During its descent, the spacecraft would keep its high-gain antenna pointed at Earth to transmit images and other science data as quickly as possible. Although the landing idea would definitely attract considerable media attention, several key members of the *NEAR Shoemaker* team were worried that a failure would tarnish the favorable impression of *NEAR Shoemaker*'s earlier successes.

On the other hand, supporters of the landing option argued that this was too good an opportunity to pass up. If everything went according to plan, images of Eros' surface with resolutions 10–20× better than anything obtained earlier would be acquired. Because the images would be returned during the descent, success would not depend on the spacecraft surviving the landing impact.

After listening to all the arguments, both pro and con, NASA decided in favor of a "controlled descent" to Eros' surface. The primary goal of the controlled descent was to obtain high-resolution images. A secondary goal was to achieve a soft landing (i.e., an impact velocity <3 m/s). There was also a slight hope that the spacecraft would survive the landing and transmit a signal from the surface.

In preparation for the descent phase, *NEAR Shoemaker* was placed into a near-circular 36-km orbit on January 28. A deorbit maneuver at about 10:30 a.m. EST on February 12 began *NEAR Shoemaker*'s descent to a targeted region near the edge of the large Himeros depression (Fig. 6). Approximately 3 h and 45 min later, the first of four braking maneuvers was initiated. This maneuver occurred at an altitude of roughly 5 km, and slowed *NEAR Shoemaker*'s rate of descent by about 6 m/s. After three more braking maneuvers, *NEAR Shoemaker* touched down on the surface of Eros at 3:01:51 p.m. EST.

The final 46 min of the descent profile is shown in Fig. 7. Measurements from the laser rangefinder indicated that *NEAR Shoemaker*'s braking maneuvers were very close to nominal. The nearly perfect maneuver performance resulted in a vertical impact velocity somewhere between 1.5 and 1.8 m/s and a transverse velocity of 0.2–0.3 m/s. This was less than the 2.4-m/s impact velocity for *Viking 1*, and could be the lowest ever. In any case, *NEAR Shoemaker*'s touchdown on Eros was definitely a soft landing and not the "controlled crash" that some had predicted.

During its descent, *NEAR Shoemaker* returned 69 images of Eros, the last one snapped just 125 m above the surface (*Veverka et al.,* 2001b). As the spacecraft reached altitudes below 1 km (resolution ~50 cm), local differences in surface texture became evident. The morphology of the surface remained generally blocky, but smoother, more block-free areas appeared. The final sequence of images showed a clear transition from a blocky surface to a very smooth "pond" area. The last image had a resolution of 1–2 cm.

Although telemetry ceased when the spacecraft hit Eros' surface, carrier lock was maintained, indicating that *NEAR*

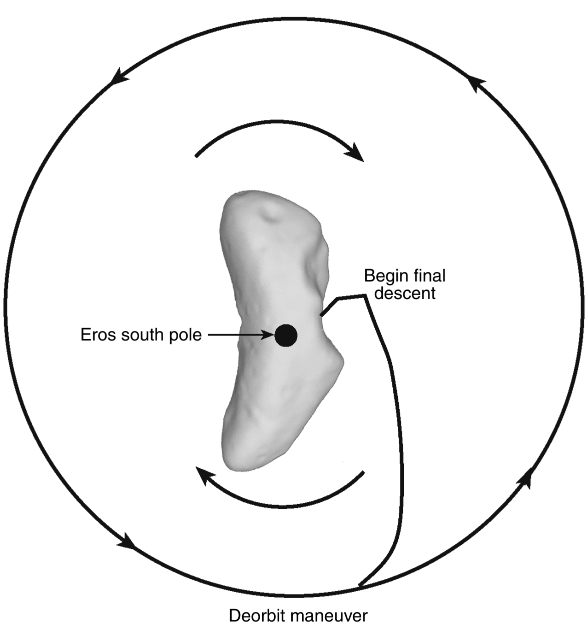

Fig. 6. *NEAR Shoemaker*'s descent from 36-km orbit (view from Sun).

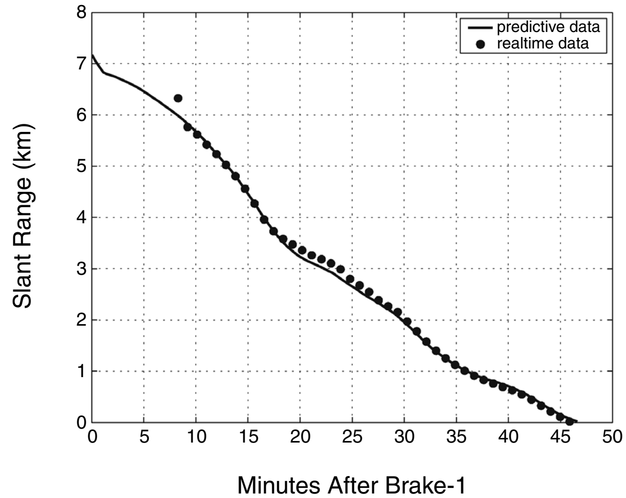

Fig. 7. *NEAR Shoemaker*'s descent profile, slant range vs. time (at start, slant range ~7 km and altitude ~5 km).

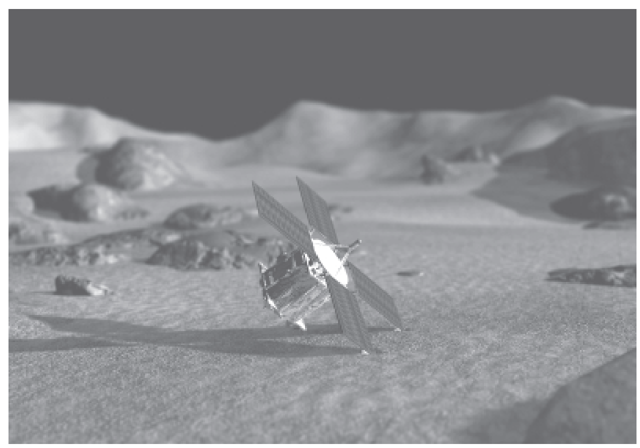

Fig. 8. *NEAR Shoemaker* on Eros' surface.

TABLE 3. Planetary landers: Historic firsts.

February 3, 1966	Moon	*Luna 9*	USSR
December 15, 1970	Venus	*Venera 7*	USSR
December 2, 1971	Mars	*Mars 3*	USSR
February 12, 2001	Eros	*NEAR*	USA

Shoemaker was still operational. Apparently, the attitude control thrusters tried to keep the high-gain antenna pointed at the Earth, but could not achieve the accuracy needed to support the telemetry link. In any case, the remaining fuel was soon exhausted, and the spacecraft dropped into its final resting on the tips of two solar panels and the bottom edge of the main body (Fig. 8).

Sometime later, *NEAR Shoemaker* automatically switched to its forward low-gain antenna, and a tenuous 10-bps telemetry link was established. Even at this low data rate, it was found that useful surface science could be obtained from two instruments, the γ-ray spectrometer and the magnetometer. The possibility of gathering additional data from the γ-ray spectrometer was especially attractive because of its vastly improved sensitivity on Eros' surface. Therefore, NASA decided to extend *NEAR Shoemaker*'s mission by 14 d. This decision proved to be very wise because the surface data obtained by the γ-ray instrument was far better than all its earlier orbital data (*Sky & Telescope*, May 2001).

NEAR Shoemaker was the first mission in NASA's Discovery Program of low-cost planetary missions. During its 5-year mission, *NEAR Shoemaker* has racked up an impressive list of "firsts": (1) first spacecraft powered by solar cells to operate beyond Mars orbit; (2) first encounter with a C-class asteroid (June 27, 1997); (3) first encounter with a near-Earth asteroid (December 23, 1998); (4) first spacecraft to orbit a small body (February 14, 2000); (5) first spacecraft to land on a small body (February 12, 2001). The final "first" was especially significant because this was the first time that a U.S. spacecraft was the first to land on a solar system body (Table 3).

TABLE 4. *MUSES-C* mission timeline.

	1998 SF36	1989 ML
Launch window	Nov.–Dec. 2002	July 2002
	May 2003	
Arrival at asteroid	June 2005	October 2003
	(L + 30/25 months)	(L + 25 months)
Depart from asteroid	November 2005	March 2004
	(L + 35/30 months)	(L + 20 months)
Return to Earth	June 2007	June 2006
	(L + 54/49 months)	(L + 47 months)
Sun–s/c distance	0.95–1.20 AU	1.11–1.33 AU
Earth–s/c distance	1.93–2.13 AU	1.86–2.33 AU
Sun–s/c–Earth angle	3.5°–8.8°	8.7°–26.4°
Max. Sun–s/c distance	1.69 AU	1.44 AU
Min. Sun–s/c distance	0.88 AU	1.00 AU
Max. Earth–s/c distance	2.52 AU	2.44 AU

4. *MUSES-C* SAMPLE-RETURN MISSION

Japan's Institute of Space and Astronautical Science (ISAS) and NASA have agreed to cooperate on the first space mission to collect asteroid surface samples and return them to Earth for detailed compositional analyses. Current plans include the launch of the *MUSES-C* spacecraft via the MV launch vehicle from the Kagoshima Space Center, Japan, in November or December 2002 (*Kawaguchi et al.,* 2000). After an Earth swingby in May 2004, the spacecraft will rendezvous with near-Earth asteroid 1998 SF36 in June 2005. After a stay of about 5 months, *MUSES-C* will return to Earth in June 2007 with an asteroid surface sample of a few grams (Table 4). The ISAS Project Manager and Project Scientist are Drs. Jun Kawaguchi and Akira Fujiwara respectively. ISAS is responsible for the mission management, mission design, and operations as well as spacecraft development. NASA participation involves spacecraft tracking by NASA's Deep Space Network (DSN), some navigation support, and participation on the *MUSES-C* science team.

The *MUSES-C* mission is primarily a test flight for four new technologies, including (1) a demonstration of the four ion engines in interplanetary space for up to 18,000 h; (2) the use of optical navigation images to autonomously guide the spacecraft during the asteroid rendezvous; (3) a demonstration of a sample collection device for surface materials retrieval; (4) a demonstration of the sample capsule's ability to effect an Earth atmosphere entry directly from an interplanetary trajectory.

The entire spacecraft is shown in Fig. 9. It is a three-axis stabilized spacecraft whose nominal attitude is pointed to the Sun, so that the solar power can be extracted as much as possible for driving the ion engines. The 1.6-m-diameter high-gain antenna (HGA) is placed atop the spacecraft. The X-band up and down links are baselined with two receivers and one transmitter whose output is boosted by two power amplifiers. Two medium-gain horn antennas (MGA) are mounted on the spacecraft inclined to the HGA radiative direction. One MGA is gimbaled to ensure the downlink communication, while the ion engines are driven toward the prescribed acceleration direction.

While the science objectives are secondary to the technologies being tested, the planned science return is very impressive. The asteroid surface samples will be studied ex-

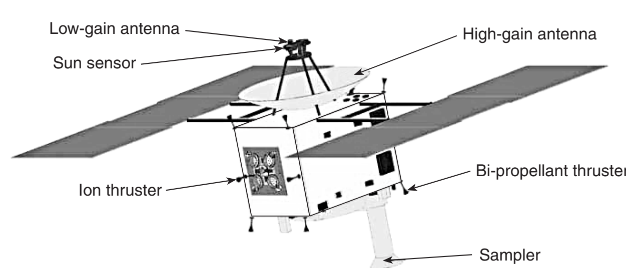

Fig. 9. *MUSES-C* spacecraft.

TABLE 5. Target asteroids for *MUSES-C*.

	1998 SF36	1989 ML
Physical Characteristics		
Magnitude (abs.)	19.1	19.5
Type	S	C, E, or M
Albedo	0.32	0.04–0.4
Diameter (average)	0.36 km	0.25–0.80 km
Major/minor axis ratio	1–2.5 (?)	1.7–2.5
Density	1–3 g/cm^3	1–3 g/cm^3
Rotation period	12 h	~19 h
Temperature at subsolar point	217–445 K	410 K
Orbital Elements		
Semimajor axis (AU)	1.324	1.273
Eccentricity	0.280	0.137
Inclination (degrees)	1.72	4.38
Perihelion (AU)	0.95	1.10
Aphelion (AU)	1.62	1.45
Period (yr)	1.52	1.43

tensively by an international group of scientists in an effort to establish a link between the parent asteroid's spectral type (S-type) and the meteorite type that is compositionally most similar to the asteroid's surface samples. Once this link is forged between an S-type asteroid and the most likely meteorite analog, future ground-based observations could be used to infer the chemical composition of any asteroid that has the spectral classification of asteroid 1998 SF36.

The orbit of the *MUSES-C* target body, 1998 SF36, has a low inclination with respect to the ecliptic plane (1.7°) so that it is one of the more accessible asteroids for a spacecraft rendezvous. Fortunately, this asteroid made a close Earth approach to within 6,000,000 km in late March 2001 and will make an even closer Earth approach to within 2,000,000 km in late June 2004. Optical, infrared, and radar observations were undertaken in March 2001 and the object appears to have a diameter of about 360 m, and an S-type spectra analogous to that of a LL ordinary chondrite. Additional observations, planned for June 2004, will be used to further characterize the shape and spin axis orientation of the target body. Table 5 provides the orbital and physical characteristics for the primary mission target asteroid, 1998 SF36, and the backup target asteroid, (10302) 1989 ML.

As well as the science benefits to be derived from the returned surface samples, the *MUSES-C* spacecraft carries an impressive array of instruments to study the asteroid *in situ*. The *MUSES-C* spacecraft's science instruments and their science objectives are:

AMICA — Asteroid Multiband Imaging Camera (T. Nakamura, Team Leader)

- Characterize the surface morphology and the processes that affect the asteroid's surface
- Determine the global size, shape, and volume of asteroid
- Determine the asteroid's spin rate
- Establish a global map of surface features and colors
- Reveal the history of impacts from other asteroid and comet fragments
- Search for possible asteroid satellites and dust rings
- Determine optical parameters of regolith particles using polarization degree vs. phase curve at large phase angles

LIDAR (T. Mukai, Team Leader)

- Provide accurate shape and mass determinations
- Map the asteroid's surface with a maximum resolution of about 1 m
- Map global surface albedo at a wavelength of 1 μm

X-Ray Spectrometer — XRS (M. Kato, Team Leader)

- Map the major-element composition of the surface as the asteroid rotates under the spacecraft
- Determine the major-element composition at localized areas during asteroid approach phase
- Measure surface composition accurately enough to establish relationship between asteroids and meteorites and identify type of meteorite to which asteroid is linked
- Provide elemental abundance maps to investigate inhomogeneity of regolith
- Characterize surface heterogeneity

Near-IR Spectrometer (M. Abe, Team Leader)

- Map mineralogic composition of asteroid and provide evidence for the rock types present on the surface at scales as small as 20 m
- Together with elemental composition measurements provided by the XRS and color imagery from the camera, the provide link between asteroids and meteorites

In addition to the above four instruments, the spacecraft has a laser rangefinder (LRF), a star tracker, two wide-angle cameras, a surface sampling device, and possibly a surface hopper.

The LRF targets a reflector on the spacecraft sampling horn so that when the horn is deformed upon touching the

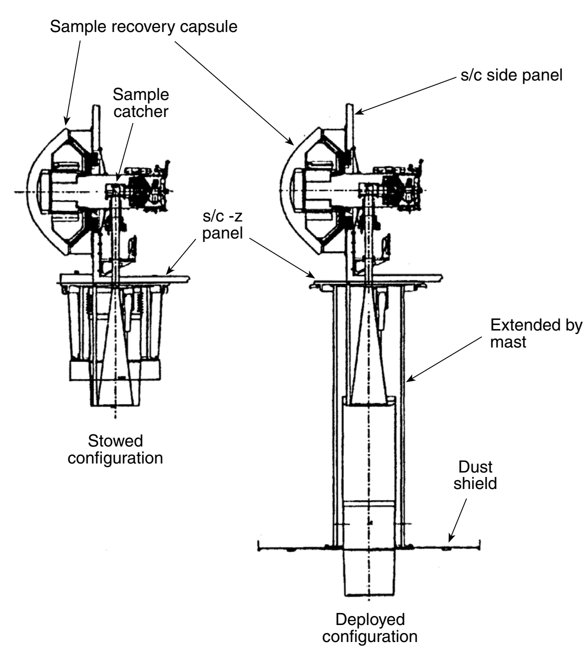

Fig. 10. Capsule and sample collector.

asteroid's surface, the sampling sequence begins. One wide-angle camera will be used for navigation during the spacecraft touchdown sequences while the other will be used as a backup for the star tracker and also for science observations in the terminator region.

The surface sampling will be carried out using one or more pellets fired into the asteroid's surface. The surface ejecta will then be captured when a collecting horn funnels the ejecta to an onboard sample catcher (Fig. 10). This catcher is a canister with separate compartments and once the sampling process is complete, the canister is pushed into an Earth reentry vehicle (40 cm diameter) that eventually makes a direct entry into the Earth's atmosphere. Equipped with a heat shield, the sample return capsule then parachutes down to the recovery site. After an international proposal process, a portion of the few grams of asteroid surface sample will then be made available for scientific study.

One mission option includes a technology test of an asteroid surface hopper (*MINERVA*) equipped with a visible wide-angle imager. The design mass of this surface hopper is only 1 kg and it is equipped with a turntable for orientation and a torque wheel device that provides the necessary hopping motion.

5. THE *DAWN* MISSION: A RENDEZVOUS WITH VESTA AND CERES

Dawn is a Discovery-class mission, approved for development as this volume was in press and scheduled for launch in May 2006. In the *Asteroids II* volume (*Veverka et al.,* 1989) a multiple main-belt asteroid orbiter/flyby was described as the "asteroid gem of the Solar System Exploration Committee (SSEC) program." The objectives of such a mission, as listed in the *SSEC Report* (1983), were to (1) characterize asteroids of various types including determinations of size, shape, rotation, albedo, mass, density, surface morphology, surface composition magnetic field and solar wind interaction; and (2) provide a more detailed study of one or more selected main belt asteroids, emphasizing elemental and mineralogical composition and detailed morphology."

At that time the suggested instruments to be carried on such a multiple asteroid mission and their measurement objectives were:

Imaging	*Size, shape rotation, surface morphology*
X-ray and γ-ray spectrometer	Elemental composition
IR reflectance spectral mapper	Mineralogical composition
Magnetometer	Intrinsic magnetic field; nature of solar wind interaction
Radio science	Mass determination

As conceived in 1983 this mission would rendezvous with a main-belt asteroid and spend 2 months in orbit. It would then fly by several other asteroids, hopefully to rendezvous with a second asteroid.

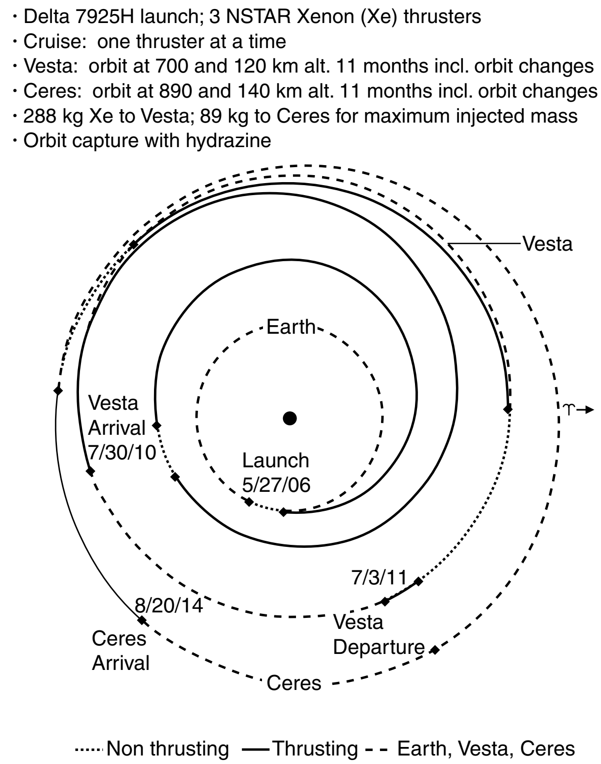

Fig. 11. *Dawn* mission overview and trajectory profile.

The *Dawn* mission was very consciously designed to address the SSEC science objectives for the main belt. An important advance over the intervening years is that it can now use solar electric propulsion, flight qualified on the *Deep Space 1* mission to rendezvous with and orbit for 11 months at each of Vesta and Ceres, the two most massive main-belt asteroids and possibly the only unshattered survivors of the original planetesimals *(Bell,* 1989). A mission overview and trajectory profile for the *Dawn* mission is given in Fig. 11. In the course of its interplanetary trajectory it can be directed to pass arbitrarily close to up to a dozen asteroids. The exact number will be chosen to maximize science return while maintaining simplicity of operations and prudent fuel reserves. The *Dawn* payload does not include an X-ray spectrometer as its γ-ray/neutron spectrometer returns similar information for lower cost and fewer spacecraft resources and because the X-ray measurement becomes less sensitive with increasing distance from the Sun and at times at low solar activity. The *Dawn* payload instead includes a laser altimeter in recognition of the valuable contribution of this instrument to the study of the Moon on the *Clementine* mission, to Mars on the *Mars Global Surveyor* mission, and to Eros on the *NEAR Shoemaker* mission.

Ceres appears to have retained its primordial structure while Vesta has differentiated and formed a core. The relative water content of Ceres and Vesta may have played an important role in allowing such different thermal evolutions. Thus *Dawn* has the added objective of determining the role of water in asteroidal evolution.

An important aspect of the *Dawn* mission will be the involvement of the asteroid and meteorite communities. This will be facilitated through *Dawn*'s participating scientist and data analysis programs over the course of the mission. Open communications and collaborative opportunities with the science team will be a hallmark of the *Dawn* project.

After launch in May 2006, Dawn cruises for four years arriving at Vesta in July 2010. The spacecraft would then leave in July 2011 and arrive at Ceres in August 2014. The *Dawn* science team (A. Coradini, W. C. Feldman, R. Jaumann, A. S. Konopliv, T. B. McCord, L. A. McFadden, H. Y. McSween, S. Mottola, G. Neukum, C. M. Pieters, C. A. Raymond, C. T. Russell, D. E. Smith, M. V. Sykes, B. Williams, and M. T. Zuber) look forward to being able to undertake this mission, which we expect to set new standards for science return by a Discovery-class mission.

REFERENCES

Barucci M. A., Doressoundiram A., Fulchignoni M., Florczak M., Lazzarin M., and Angeli C. (1998) Compositional type characterization of Rosetta asteroid candidates. *Planet. Space Sci., 46,* 75–82.

Bell J. (1989) Asteroids: The big picture. In *Asteroids II* (R. P. Binzel et al., eds.), pp. 921–945. Univ. of Arizona, Tucson.

Belton M. J. S., Chapman C. R., Klaasen K. P., Harch A. P., Thomas P. C., Veverka J., McEwen A. S., and Pappalardo R. T. (1996) Galileo's encounter with 243 Ida: An overview of the imaging experiment. *Icarus, 120,* 1–19.

Dunham D. W., Farquhar R. W., McAdams J. V., Williams B. G., Miller J. K., Helfrich C. L., Antreasian P. G., and Owen W. (2000) Recovery of NEAR's mission to Eros. *Acta Astron., 47,* 503–512.

Kawaguchi J., Uesugi K., and Fujiwara A. (2000) Project status of the MUSES-C sample and return from an asteroid. *IAA Paper 00-11.2.01,* paper presented at the Intl. Astronautical Congress meeting in Rio de Janeiro, Brazil.

Nozette S. and Shoemaker E. M. (1993) Back to the Moon, on to an asteroid: The Clementine mission. *The Planetary Report, 13,* 10–15.

Veverka J., Langevin Y., Farquhar R., and Fulchignoni M. (1989) Spacecraft exploration of asteroids: The 1988 perspective. In *Asteroids II* (R. P. Binzel et al., eds.), pp. 970–993. Univ. of Arizona, Tucson.

Veverka J. and 25 colleagues. (1999) Imaging of asteroid 433 Eros during NEAR's flyby reconnaissance. *Science, 285,* 562–564.

Veverka J. and 32 colleagues (2000) NEAR at Eros: Imaging and spectral results. *Science, 289,* 2088–2097.

Veverka J. and 32 colleagues (2001a) Imaging of small-scale features on 433 Eros from NEAR: Evidence for a complex regolith. *Science, 292,* 484–488.

Veverka J. and 38 colleagues (2001b) NEAR's descent to Eros: Unexpected depositional and erosional features in the regolith. *Nature,* in press.

Yeomans D. K. and 12 colleagues (1997) Estimating the mass of asteroid 253 Mathilde from tracking data during the NEAR flyby. *Science, 278,* 2106–2109.

Yeomans D. K. and 15 colleagues (2000) Radio science results during the NEAR Shoemaker spacecraft rendezvous with Eros. *Science, 289,* 2085–2088.

Zuber M. T., Smith D. E., Cheng A. F., Garvin J. B., Aharonson O., Cole T. D., Dunn P. J., Guo Y., Lemoine F. G., Neumann G. A., Rowlands D. D., and Torrence M. H. (2000) The shape of 433 Eros from the NEAR-Shoemaker laser rangefinder. *Science, 289,* 2097–2101.