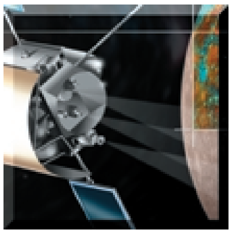


Planetary Science at APL

Andrew F. Cheng

Planetary science at APL did not begin with the Near Earth Asteroid Rendezvous (NEAR) mission, although NEAR, as the first planetary mission ever implemented by a non-NASA center, is what brought the Laboratory into the main arena of planetary exploration. This is the story of how that happened, how planetary science developed at APL, and what lies ahead. (Keywords: CONTOUR mission, Discovery Program, MESSENGER mission, NEAR mission, Planetary science.)

INTRODUCTION

Planetary science at APL began with the NASA Voyager Program, which had two launches in 1977. Voyager carried the APL Low Energy Charged Particles experiment to the outer solar system, unveiling for the first time the mysteries of the Io torus at Jupiter and discovering the magnetospheres of Uranus and Neptune. The stories of APL's contributions to Voyager, and later to the Galileo mission to Jupiter and the Cassini mission to Saturn, are given elsewhere in this issue. Our work in the study of charged particle radiation environments and electromagnetic fields is integral to planetary science, but is only one of its many disciplines. Planetary science concerns the planets themselves, their surfaces, atmospheres, interiors, and satellite systems, as well as the smaller members of the solar system such as comets, asteroids, and meteoroids. Exploration of the solar system involves learning not only about present day processes and conditions, but also about the origins of the solar system, the geologic histories of the planets and smaller bodies, and the origins of life.

APL has been a major player in the particles and fields arena from the beginning of the space age, but has become a major player in solar system exploration only recently. The story of how this happened is mainly the story of the NASA Discovery Program and the Near Earth Asteroid Rendezvous (NEAR) mission, the first planetary mission for which the spacecraft was designed, built, and operated outside of a NASA center. Although I lived through the events in question and participated in them, I am still amazed at the outcome. How did NEAR come to APL, and what lies in store for the future of planetary science at APL after NEAR?

THE DISCOVERY PROGRAM

NEAR was the first launch of the Discovery Program, and one of the first two Discovery missions approved for funding. The Discovery Program has by now seen four successful launches—NEAR, Mars Pathfinder, Lunar Prospector, and Stardust—and has recorded successful science returns from all but the last, which launched in February 1999 (NEAR, of course, has more science to come). With this string of successes in hand, the Discovery Program can truly be said to have established the "better, faster, cheaper" planetary missions as a new paradigm at NASA.

It is all too easy to forget that only 10 years ago, the conventional wisdom held "low-cost planetary mission" to be an oxymoron.[1] Those in the know at the time did not credit the Discovery Program with much chance of getting funded in the first place, and once NEAR and Mars Pathfinder were approved for new starts in 1993, neither program was thought to have much chance of success.

The background for these gloomy prognostications was laid in the early 1980s. Owing to steadily increasing pressures on the federal budget, there was increasing concern within NASA and the science community that billion-dollar–class planetary missions like Galileo would be increasingly hard to come by in the future. Galileo had recently survived a "near-death experience" in Congress and was still years away from launch. It appeared that more than a decade would elapse between the Voyager launches in 1977 and the follow-on Galileo launch (in the end, Galileo was launched in 1989). NASA decided that it was time to inaugurate a series of low-cost planetary missions, to increase the rate of launches, and to provide numerous opportunities to address focused science questions. This new series of missions would be called "Planetary Observers," of which the first would be the Mars Observer. NEAR, the first mission to orbit an asteroid, was designated as the follow-on to Mars Observer, and was the subject of a NASA-funded study[2] in 1986.

Already by the late 1980s, it became clear that Mars Observer was not destined to be a low-cost planetary mission. Its development cost had grown well beyond original projections; its instrument payload had to be descoped (leading to cancellation of an APL-developed instrument, the Mars Observer Radar Altimeter); and the 1986 Challenger disaster had forced a launch vehicle change. Ultimately, Mars Observer was launched in 1992. By the time the mission was lost in September 1993—just before insertion to Mars orbit—its total cost had exceeded $900 million.

Still, at the end of the 1980s there was a strong push within NASA and the science community to find some way for NASA to implement low-cost planetary missions. There was also a sense that continued cost overruns and mission delays would threaten the future of space science and that the science community could not long survive a mission frequency of one per decade. In 1989, within the ongoing NASA strategic planning activities, a small mission planning group was convened to find solutions. Stamatios (Tom) Krimigis of the APL Space Department has recounted how, as a member of that group, he presented a briefing to NASA that identified an appropriate model within NASA experience for a new line of low-cost planetary missions, namely, the Explorer Program[1] (and not Mars Observer). He cited as a specific example the Advanced Composition Explorer (ACE) that had just been selected by NASA for flight (ACE, as it turned out, was launched successfully in 1997 and is still operating) as well as the Active Magnetospheric Particle Tracer Explorer (AMPTE) mission that had recently been completed successfully.

Subsequently, NASA established a science working group to define a low-cost planetary mission plan. This group met during 1989 to 1990 and recommended that NASA establish a new program to be called "Discovery." A new Director for Solar System Exploration at NASA, Wesley Huntress, reconstituted the group in 1990 under the chairmanship of Joseph Veverka (Cornell University) and charged it to make specific mission recommendations. The group decided to study the NEAR mission, building upon the report[2] of the earlier 1986 science working group (also chaired by Veverka) that had endorsed NEAR as an essential component of NASA's planetary exploration program. NASA funded two competing studies, one at APL and one at the Jet Propulsion Laboratory (JPL), on the feasibility of NEAR within a development cost of less than $150 million.

At this time, in late 1990, I became involved with NEAR. I had previously served on a number of NASA science advisory committees and working groups, and had become acquainted with the 1986 NEAR report while serving on the National Research Council Committee on Planetary and Lunar Exploration. I liked what I saw of NEAR back in 1987 and knew that there was strong support for the mission in the science community, so I was happy to sign on for the APL NEAR study when Tom Krimigis called. I did not realize then that I was signing up for a 10-year hitch.

Near Earth Asteroid Rendezvous

A small group at APL was charged with leading the NEAR concept: Thomas Coughlin as study manager, Robert Farquhar for mission design (transitioning at the time from NASA Headquarters to APL), Edward Reynolds as systems engineer, Robert Gold as the instrument lead, and myself as study scientist. Except for Reynolds (who later moved on to the CONTOUR mission, see below), all the principals have stayed with the NEAR mission from the beginning. NEAR was a small study, completed in May 1991 for under $100,000. The team was strongly motivated—we were always aware that NASA had never before actually implemented a planetary mission outside of a NASA center.

My first and primary task was defining and prioritizing mission science objectives. I felt from the outset that the 1986 NEAR science working group had defined a compelling mission, and that APL should try to come as close as possible to the 1986 concept within the $150 million development cost cap. However, we began the study without having a clearly defined scope, so we took the initial position that NEAR had to be a true rendezvous mission, achieve orbit around an asteroid, and carry at least a multispectral imager and a capable gamma ray spectrometer. We hoped we could eventually accommodate more instruments, but in the beginning we committed only to those two. I recall discussing this position with Veverka early in 1991 and coming away with the conviction that if we could succeed in this approach, we had a winning concept.

From the outset, the engineering and management members of our small team kept stressing that this spacecraft had to be simple in order to meet the cost cap. The reader may find a notebook sketch from 11 January 1991 to be of historical interest (Fig. 1). Based on the positions of the Earth, the Sun, and the target asteroid (Anteros, at that time), we convinced ourselves that NEAR could be configured with a fixed high gain antenna, fixed solar panels, fixed instruments with a common boresight orthogonal to the antenna axis, and a rocket engine thrusting opposite to the instrument boresight. With this simple spacecraft, we could accomplish all the science objectives of the mission. (For comparison, the Mars Observer had articulated solar panels, an articulated high gain antenna, and several instruments with scan mirrors.)

In the end, the APL study team concluded that NEAR could indeed be accomplished with a simple spacecraft and mission concept similar to that early sketch. The study was completed in May 1991, and Fig. 2 shows a page from the study report. Also reproduced from the study is our proposed development schedule (Fig. 3).

The 1991 APL NEAR study was presented to NASA and the Discovery science working group at a meeting in Pasadena, California. Results of the competing study performed by JPL were also presented. Our development schedule showed implementation beginning at the end of 1993 and launch in May 1997. I recall the reaction of several meeting participants to this schedule—not so much skepticism as amusement. As things turned out, we did indeed begin implementation in December 1993, but we launched in February 1996, more than a year earlier than planned in 1991!

The APL study had concluded that it was feasible within the $150

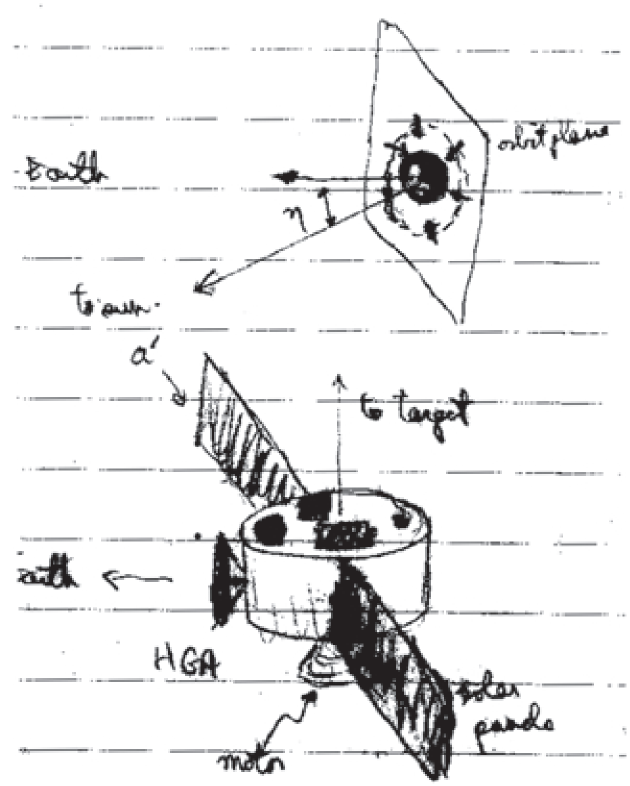
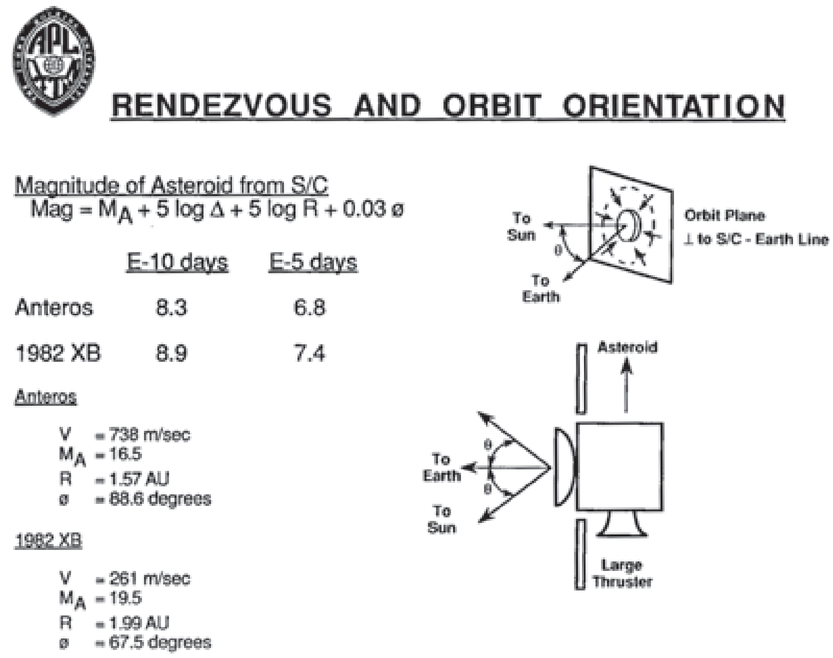


Figure 1. January 1991 sketch from an APL laboratory notebook showing how a simple spacecraft could be configured to accomplish the NEAR mission.



RENDEZVOUS AND ORBIT ORIENTATION

Magnitude of Asteroid from S/C
$Mag = M_A + 5 \log \Delta + 5 \log R + 0.03 ø$

	E-10 days	E-5 days
Anteros	8.3	6.8
1982 XB	8.9	7.4

Anteros
V = 738 m/sec
M_A = 16.5
R = 1.57 AU
ø = 88.6 degrees

1982 XB
V = 261 m/sec
M_A = 19.5
R = 1.99 AU
ø = 67.5 degrees

Figure 2. A page reproduced from the May 1991 APL study report as presented to NASA. At the time, the 1996 Eros launch opportunity had not yet been identified for the NEAR mission, but the spacecraft and mission concept had largely taken shape.

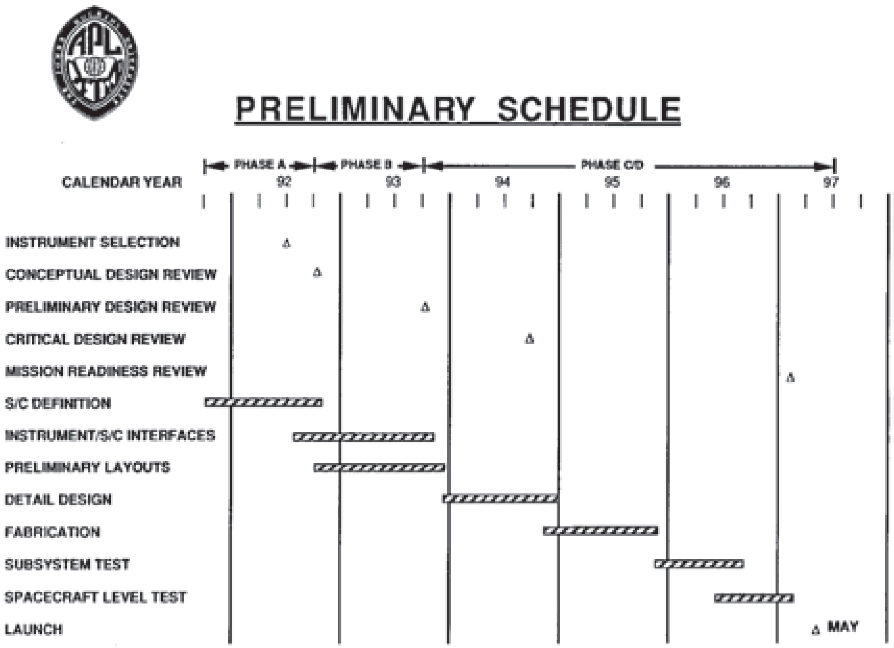


Figure 3. The original schedule for the NEAR mission as proposed in May 1991. This schedule was regarded as extremely aggressive, but NEAR actually was launched in February 1996.

million cost cap for NEAR to orbit an asteroid and carry five instruments, i.e., a multispectral imager, an imaging spectrograph, a gamma ray spectrometer, a laser altimeter, and a magnetometer. The JPL study had reached a very different conclusion: the NEAR mission was unlikely to be accomplished as a single launch within the $150 million cost cap, and a sequence of launches was proposed, beginning with asteroid flybys carrying only imaging systems and culminating with an asteroid orbiter mission. The Discovery science working group, plus a group of senior NASA managers appointed by Wesley Huntress, concluded that the APL approach was preferable. Subsequently, the JPL study team revisited its results and concluded that the NEAR mission was indeed feasible within the cost cap. On the basis of results from JPL and APL, Huntress decided to inaugurate the Discovery Program of low-cost planetary missions in the 1991 strategic plan for solar system exploration, with NEAR to be the first mission.

I recall feeling elated at this turn of events, and I believe the reaction at JPL was similar. Still, all of us at both APL and JPL knew that the outcome was far from decided. Before the new Discovery Program could become a reality, and before NEAR could be implemented anywhere, the administration had to concur and Congress had to vote funding. I am sure that no one at NASA or in the science community expected at the time (mid-1991) that an APL NEAR mission would be implemented any time within the next few years. However, prospects for the Discovery Program were much better than anticipated because of strong interest and support from Huntress and others at NASA as well as within Congress.

Events soon appeared to confirm our expectations. The FY92 Senate appropriations bill directed NASA to prepare a plan to "develop small planetary or other space science missions." NASA prepared the plan and submitted it to Congress in April 1992. The plan proposed a sequence of two missions to inaugurate the Discovery Program, and the first mission would be a Mars lander to be called the Mars Environmental Survey (MESUR) Pathfinder (later renamed Mars Pathfinder after cancellation of the MESUR Program). This would be the only mission implemented, at the outset, by JPL. The follow-on mission, NEAR, would be implemented by APL. Implicit in this plan was that NEAR would be started if Discovery missions were proven to be feasible in the first place.

Needless to say, we were disappointed. Tom Krimigis led me and the late Thomas Potemra in making our case to NASA and to members of Congress and the Congressional staff. NEAR was the original first choice of the science community based on science merit, and it was NASA's first choice in its 1991 strategic plan. But in the fall of 1992 Robert Farquhar gave us a trump card when he found a launch opportunity to the unusually large and important asteroid 433 Eros in early 1996: this opportunity occurs only once every 7 years, and now we had a rationale for proposing that NEAR implementation begin in FY94 to take advantage of the 1996 launch opportunity. Previously, the view at NASA was that launch in any year was feasible for NEAR because numerous potential asteroid rendezvous targets existed.

Congress gave FY93 preproject funding for continued work on the two Discovery mission concepts. NASA agreed to request new starts for both Pathfinder and NEAR in the FY94 budget, allowing implementation of each mission to begin simultaneously. Obviously, simultaneous implementation would require a higher rate of funding. Congress concurred and came through with funding at this higher level. NEAR began implementation in December 1993, just as we had rashly predicted in May 1991!

So how did we feel in the aftermath of these events? Of course we were grateful for the outcome, but I remember more a feeling of amazement. As it turned out, Congress's action was fruitful. Both NEAR and Mars Pathfinder have been outstanding successes, and the Discovery Program has now become the mainstay of planetary exploration.

The NEAR spacecraft was developed in 27 months and was launched successfully on 17 February 1996. Details of how the spacecraft and instruments came together have been described in a previous issue of the *Technical Digest* (**19**(2), 1998). Although there is more to the story—how the mission and the payload were defined, how the science team was selected—at this point I shall skip ahead to the science highlights of the NEAR mission to date.

Principal among these highlights is the NEAR flyby of the asteroid 253 Mathilde in 1997. Bob Farquhar, now the NEAR Mission Manager, realized that the 1996 Eros launch opportunity also enabled a flyby of Mathilde without a large fuel penalty.[3] Mathilde was a large C asteroid, a type never before encountered by a spacecraft. The announcement that Mathilde was a potential NEAR flyby target stimulated planetary scientists to make new telescopic observations, which revealed Mathilde to have an unusually long rotation period of 17.4 days, more than 20 times longer than typical asteroids. Although NEAR was late in its development phase, the Mathilde flyby was added to the mission. The NEAR spacecraft had already been designed to rendezvous with 433 Eros, to enter a low-altitude orbit around it, and to study it for a year. With the NEAR launch only months away, no changes to the spacecraft hardware or software could be made to accommodate the Mathilde flyby. NEAR's imager, in particular, was body-mounted and optimized for observations from low-altitude orbit as opposed to a fast, 10-km/s flyby. Moreover, the Mathilde flyby would occur at a point close to the mission aphelion of 2.2 AU. The spacecraft was designed only to survive at that distance from the Sun, but would now need to execute a science sequence while performing a compound rotation to track its target during the flyby. Furthermore, the Mathilde flyby would occur at an unfavorable approach phase angle of 140°, so the spacecraft could image Mathilde only by pulling the solar panels about 50° away from full illumination. Hence, power margins would be tight.

Despite these constraints, NEAR performed splendidly at Mathilde, and the flyby was a great success. Because of the tight power margins, all instruments, except for the imager, were powered off during the flyby. NEAR returned 537 images (Fig. 4) and made the first direct measurement of the mass of a C asteroid. Mathilde's density was determined to be surprisingly low, only 1.3 g/cc, indicating a porosity of at least 50% (that is, Mathilde's volume is at least half void space). The images also revealed several giant craters up to 33 km wide on a body itself only 46 × 48 × 66 km in size. How could so many craters this large have formed on poor, battered Mathilde?

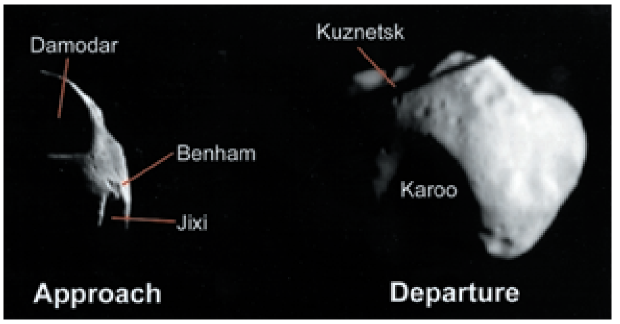


Figure 4. Two views of the asteroid 253 Mathilde, on approach and departure of NEAR. The giant craters, such as Damodar and Karoo, are deeply shadowed and are responsible for Mathilde's bizarre appearance. Karoo, the largest known crater on Mathilde, is 33 km in diameter. Features on Mathilde are named after coal fields on Earth.

Next up for NEAR is the rendezvous with Eros, which was originally scheduled for January 1999. NEAR's rendezvous burn on 20 December 1998 aborted, and it executed a flyby of Eros on 23 December 1998. The rendezvous burn was accomplished successfully on 3 January 1999, and the spacecraft is now targeted for rendezvous on 14 February 2000. NEAR returned 222 images from the Eros flyby and determined the asteroid's density to be 2.5 g/cc (Eros is less porous than Mathilde). During the Eros rendezvous, NEAR will make comprehensive measurements from orbits as low as 35 km from the asteroid's center (Fig. 5). All of the original rendezvous science objectives will be accomplished.

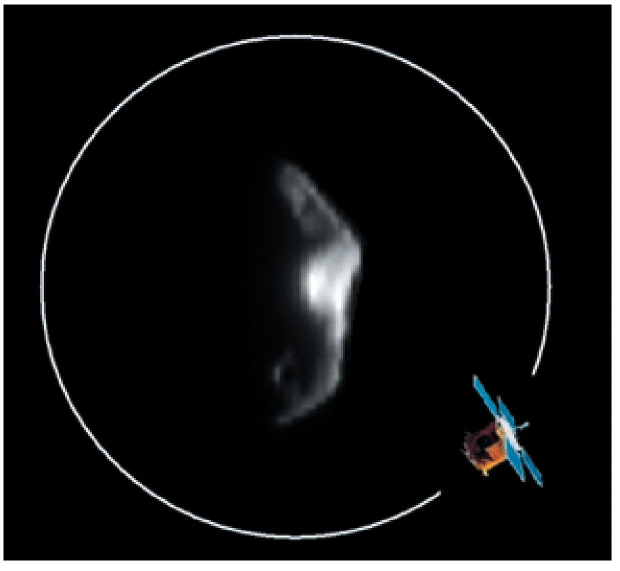


Figure 5. NEAR's 35-km orbit around Eros (asteroid and orbit to scale) with an Eros image obtained by NEAR in December 1998.

The CONTOUR Mission

Although NEAR is not yet over, APL is already starting work on its second Discovery mission, CONTOUR (Comet Nucleus Tour). After the turbulent process that resulted in selection of the first two Discovery missions, NEAR and Mars Pathfinder, NASA resolved that future Discovery missions would be chosen by open competition. CONTOUR was selected in 1998 as the sixth Discovery mission. It is a multiple comet flyby mission (Fig. 6) that will return high-resolution images of comet nuclei. CONTOUR will be launched in 2002 and encounter three very diverse comets: first the unusual, evolved Encke; then Schwassman-Wachman 3 (SW-3), which actually split into pieces in 1995; and finally d'Arrest. The CONTOUR targets, therefore, include comets in both youth and old age. The Encke encounter will occur in November 2003, the SW-3 encounter in June 2006, and the d'Arrest encounter in August 2008. CONTOUR has an interesting option, i.e., the possibility of encountering a new comet that has never passed close to the Sun, if a suitable target is discovered. CONTOUR will carry a capable remote sensing suite with autonomous target-tracking capability, obtaining high-resolution visible and near-infrared images and spectra, plus instruments to measure the composition of neutral gas, ions, and dust particles near the comet.

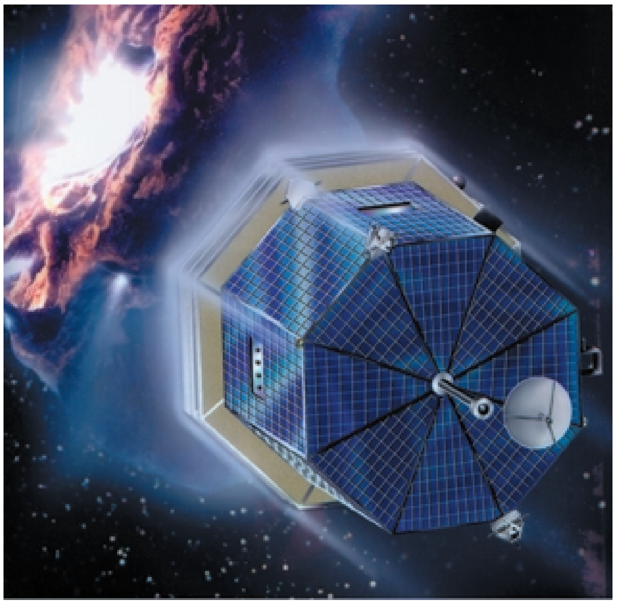


Figure 6. Artist's concept of the CONTOUR spacecraft approaching a comet nucleus.

CONTOUR's Principal Investigator, Joe Veverka, worked with us on NEAR also. APL is responsible for providing the remote sensing suite, for designing and integrating the spacecraft, and for implementing mission design and mission operations. Two planetary scientists from APL are members of the CONTOUR science team.

A LOOK AHEAD

Beyond NEAR and CONTOUR are many more challenges in planetary science for APL. I did not have space here to describe our continuing involvement in the Mars Pathfinder mission, which landed a small planetary rover successfully on 4 July 1997, and on which Scott Murchie of the APL Space Physics Group served as a member of the science team. Planetary science at APL also includes three ongoing NASA-funded instrument development programs: a miniature camera system, a laser time-of-flight mass spectrometer, and a rock chipper. APL planetary scientists have played a key role in another future Discovery mission, MESSENGER, which has just been selected for implementation by NASA. This is a mission to rendezvous with Mercury in September 2009 (Principal Investigator, Sean Solomon of the Carnegie Institute) and to carry out comprehensive measurements for a full Earth year. Laboratory scientists on MESSENGER will support numerous investigations of Mercury's surface, composition, magnetic field, tenuous atmosphere, and particle radiation environment. I will also serve as a NASA-funded investigator on the science team for the Japanese MUSES-C mission to return samples from a near-Earth asteroid and to land a 2-kg planetary rover (supplied by JPL) on its surface. Planetary scientists at APL are looking forward to an exciting future.

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