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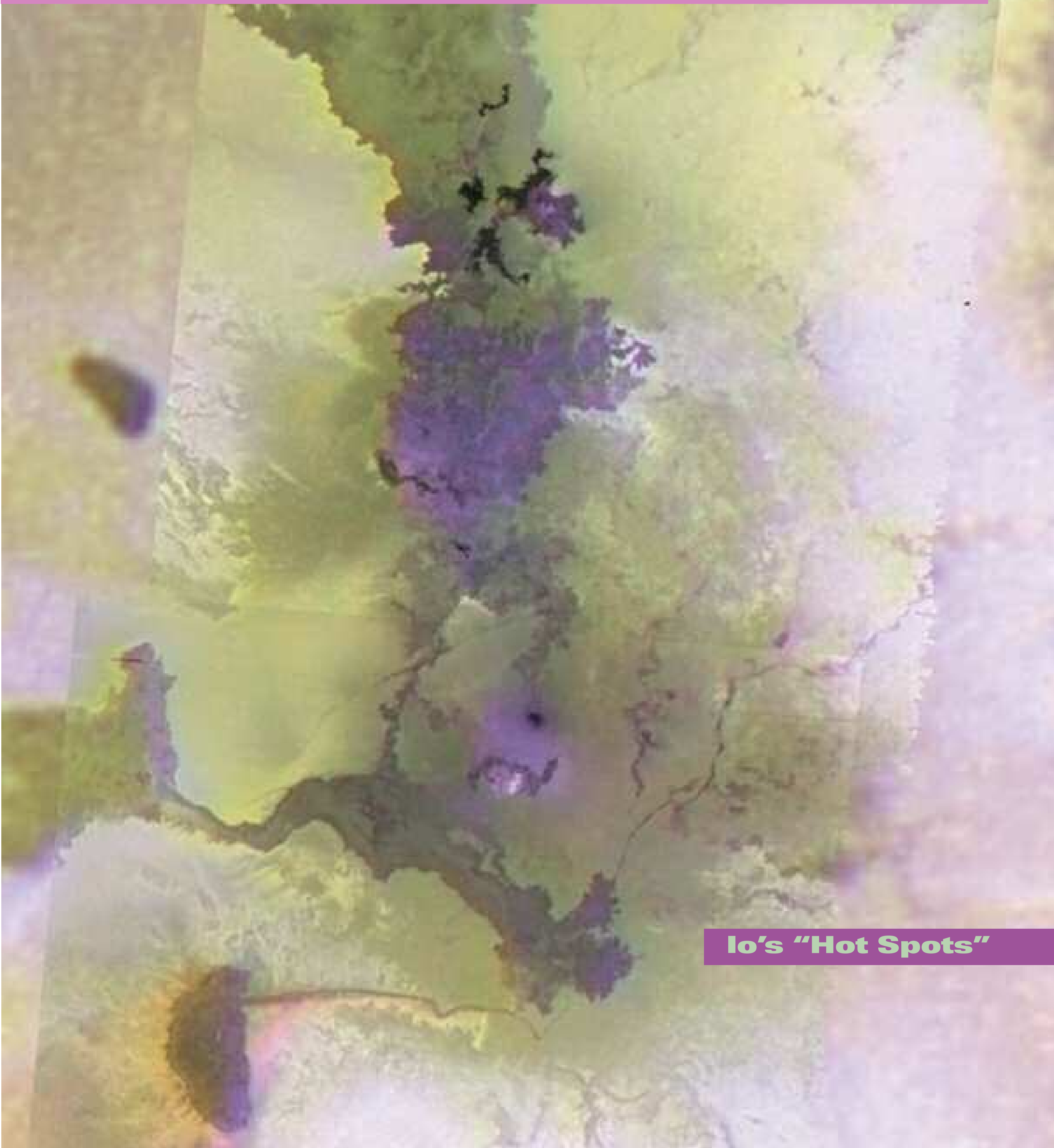

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Table of Contents

Volume XXII
Number 2
March/April 2002

From The Editor

We're gearing up for a surge of activity at The Planetary Society. For a start, *Mars Odyssey* has reached its mapping orbit and is returning detailed data about the surface of Mars. As we go to press, NASA has released initial results based on the data—and all indications are that *Mars Odyssey* is going to be a doozy of a mission. Scientists are already seeing strong evidence of hydrogen, probably from water-ice, on or near the planet's surface. You can count on many more announcements about the mission in future issues of *The Planetary Report*.

On the political front, we're preparing once again to engage Washington policy makers over restoring the mission to Pluto. Also this year, the Europa orbiter mission has been canceled. NASA now has no program to explore the outer planets of our solar system. You can read the details of the Bush administration's fiscal year 2003 budget, from which both missions are eliminated, in World Watch (page 18).

That's how it is at The Planetary Society. Sometimes, we revel in the astounding discoveries of planetary missions; other times, we fight to keep those missions alive. If you have Internet access, you can regularly check our website, *planetary.org*, for updates. In the coming weeks, we will be planning how best to return outer planet exploration to the NASA agenda. We should all be ready to act.

—Charlene M. Anderson

On the Cover:

This *Galileo* mosaic may resemble an abstract painting but is actually a high-resolution image of the longest known active lava flow in the solar system. Found in the Amirani region of Jupiter's moon Io, this flow extends roughly 350 kilometers (220 miles). Approximately half the length of the flow is shown here. Dark areas indicate recent, fresh lava; these areas are too hot to be covered by sulfur dioxide, which appears lighter. Scientists think the main Amirani plume emanates from the fuzzy purplish area near the bottom of the image.

Image: JPL/NASA

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Members' Dialogue

Sounding Off

I was once a member of The Planetary Society, but I allowed my membership to expire because I do not believe we should be pursuing a manned mission to Mars. It is premature.

I do support a constellation of satellites around Mars, and I support robotic landers. However, I do not believe the primary science goal of such landers should be geological exploration. Rather, it should be to practice landing—consistently, safely, and accurately. We need to allow for full telemetry so we can learn from the inevitable failures. As far as human exploration goes, we should be aiming for the Moon; there is no better place to cut our teeth on manned missions.

If I were able to be heard and were given the chance to try shifting the Society's focus, I would consider becoming a member again.
—ROBERT GARDIAS,
Toronto, Ontario, Canada

There have, of course, already been six human landings on the Moon, which involved eighteen astronauts. So, one could say our teeth are well on the way to being cut. Whether we should return to the Moon before we send astronauts to Mars is the real question. The most compelling reason for human spaceflight is to explore and, in that exploration, to advance our understanding of life beyond Earth. Mars is the only planet we know of besides Earth where life might be sustainable. That is why Mars exploration is the natural goal for human spaceflight. Yet, even with that goal in mind, there remains the question of whether missions to the Moon would be way stations or milestones toward achieving that goal or whether they would be detours delaying it.

The Planetary Society does not judge the outcome of that engineering and economic tradeoff. We believe that if we adopt an international goal of human exploration of Mars, the question of interim steps can be intelligently decided and planned. These steps could include missions to the Moon.

The Society agrees that for any scientific investigation into the possibility of lunar ice at the poles or underground water on Mars, robotic probes are cost-effective. As you know, we support a vigorous program of robotic space exploration.

I suspect we agree on just about everything in the big picture, and we would be lucky to be arguing only about the details. If you want to advance your agenda, or any agenda for planetary exploration, I recommend that you rejoin The Planetary Society. Thanks for writing.
—Louis D. Friedman,
Executive Director

Our Future in Space

After reading "Whither, O Splendid Ship?" (see the January/February 2002 issue of *The Planetary Report*), I want to commend John Young and James D. Burke on their insights concerning the future of space exploration. We have such great potential for a variety of achievements, from the space station to the mining of the Moon to missions to Mars and beyond. We must do what we can to enhance our potential in space.

Crucial to all of this is the education of the public, which rests in the hands of organizations such as ours and, most important, of organizations teaching our youth.
—REX CHILDRESS,
Louisville, Kentucky

Funding Restored

NASA's reversal of its December 2001 decision to terminate the Arecibo Observatory's Near Earth Object (NEO) observation program was welcome. But NASA's level of funding for NEO study in general seems inadequate.

Cutting funding to the Arecibo Observatory would have limited our ability to obtain high-precision orbital information about NEOs. It would have eliminated one of the most effective and accurate tools for determining the size of NEOs, and that speaks volumes.

NASA's current funding levels leave much of the follow-up observations of NEOs on an ad hoc basis. Plus, the amount of funds earmarked for the Minor Planet Center—which serves as the central clearinghouse for orbital data and observations (both radar and optical)—is curtailing services and operating hours. And reducing operations at the Minor Planet Center adversely affects the vital follow-up process at a time when the rate of NEO discovery and the number of discovery surveys are increasing.
—DAVID S. DIXON,
Las Cruces, New Mexico

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Mars Odyssey: Let the Mapping Begin

by Bruce Betts

Boasting one instrument that can see at night and another that gazes into the upper meter of the Martian surface, *Mars Odyssey* has successfully begun the mapping phase of its mission. Within days of starting its mapping, it had already returned tantalizing data.

Doing Circles Around Mars

Odyssey began mapping the Red Planet on February 18, 2002. Since Mars Orbital Insertion in October 2001 (see the November/December 2001 issue of *The Planetary Report*), the spacecraft had been gradually moving into a circular orbit using a technique known as aerobraking. Aerobraking involves dipping the spacecraft into the upper atmosphere, using the increased friction to slow the craft's speed. This technique greatly saves fuel but takes time and increases risk because of uncertainties in the atmosphere and proximity to the planet. *Odyssey*, following in the tradition of *Mars Global Surveyor* (*MGS*) and similar Earth-mapping missions, uses a near-polar, circular orbit to gradually build up maps of the surface. The near-polar orbit allows the spacecraft to pass over almost the entire planet, and the nearly uniform altitude of the circular orbit allows the buildup of entire data sets with the same resolution, greatly simplifying mapping and data comparisons.

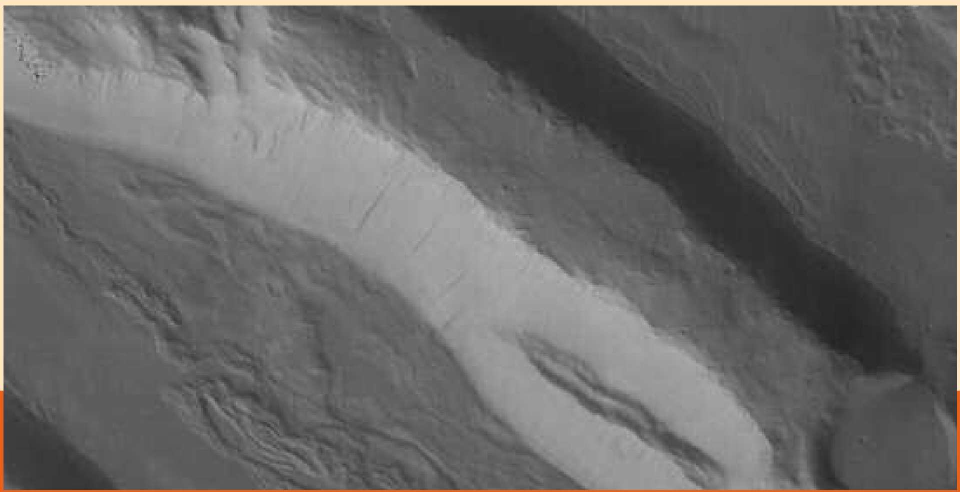
The first data from the mapping orbit were presented at a press conference at the Jet Propulsion Laboratory in early March—less than two weeks after *Odyssey* entered the mapping phase. In that time, all functioning instruments produced what appear to be excellent data, causing ecstasy among scientists associated with the mission.

Happy Data

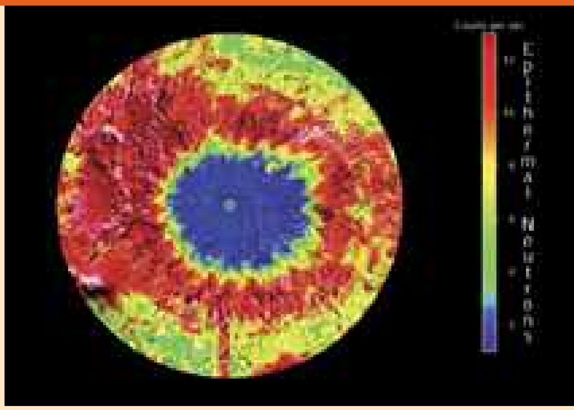
Within days of beginning its mapping orbit, *Odyssey*'s Thermal Emission Imaging System (THEMIS) produced stunning thermal infrared images. THEMIS images are basically temperature maps of the surface. Temperature indicates the physical properties of a planet's surface, including how much rock, sand, or dust it contains. This information in turn gives important clues to the evolution of the surface. THEMIS also has spectral capabilities that allow composition maps to be created from its images, much as visible color images can be produced from images taken through different-color filters. THEMIS' thermal component will map the entire surface of Mars at a resolution of 100 meters per pixel, imaging objects 30 times smaller than *MGS*'s Thermal Emission Spectrometer.

THEMIS has also produced excellent visible wavelength images. THEMIS will map at visible wavelengths at a resolution of 18 meters per pixel, which is between that of *Viking* images (usually many tens to hundreds of meters per pixel) and *MGS*'s Mars Orbiter Camera (MOC) images (1.4 meters per pixel). It can be difficult to compare features from *Viking* and MOC images because of their very different resolutions. Filling the resolution gap will greatly aid in interpreting geomorphology (the shape of geologic features). Also, though MOC images have tremendous resolution, only a small percentage of the surface has been imaged, whereas THEMIS visible images will eventually cover the entire planet at resolutions much better than *Viking*'s.

The Gamma Ray Spectrometer (GRS), which includes



This is the first visible wavelength image taken by the Thermal Emission Imaging System (THEMIS) instrument. It shows the highly fractured, faulted, and deformed Acheron Fossae region of Mars. The scarps visible in this image are approximately 1 kilometer (0.6 mile) high. Dark streaks merely 50 meters across can be seen on some cliff faces. These streaks may form when the pervasive dust mantle covering the region gives way on steep slopes to create dust avalanches. The image also shows impact craters as small as 500 meters in diameter, as well as smooth and textured plains.



The view shown here of Mars' southern hemisphere (south pole is at center) derives from measurements made during the first week of **Mars Odyssey** *'s mapping mission using the neutron spectrometer instrument, a part of the Gamma Ray Spectrometer instrument suite. The map shows intermediate energy, or epithermal, neutrons. Soil enriched in hydrogen is indicated by the deep blue colors on the map, where a low intensity of epithermal neutrons is found. All areas south of 60 degrees south latitude are significantly depleted in these neutrons, as expected for a large amount of water-ice.*
Image: NASA/JPL/University of Arizona

two neutron spectrometers as well as the gamma ray instrument has already produced data indicating the presence of water-ice in Mars' south polar region. The two neutron spectrometers detected hydrogen; at least most of it is inferred as water-ice. (Hydrogen cannot exist by itself in any significant amount, and water-ice is consistent with models of the near-polar deposits. Still, the GRS cannot distinguish between water-ice and another contributor to the signal, such as hydrated minerals.) The gamma ray portion of the instrument suite, although its boom was not yet deployed, also detected a strong hydrogen signal.

Additionally, the gamma ray sensor detects significant amounts of gamma rays from the spacecraft itself. After calibrating the strength of this signal for the next few months, the instrument will be deployed on a boom several meters long. At that time, the instrument's sensitivity to mapping a wide range of elements will greatly increase, and the GRS will begin creating the first map of the elements comprising the Martian surface. Currently, even with the instrument positioned next to the spacecraft, the hydrogen signal from Mars is strong. For elements such as aluminum that are present in significant quantities in the spacecraft, accurate measurements of Mars will have to wait for the boom deployment.

Although finding water-ice in the near-polar regions of Mars is no big surprise, since models based on Mars conditions and geologic evidence have pointed to its existence, exactly where the ice is and how much of it exists remain unknown. The coming months of mapping will shed more light on these questions.

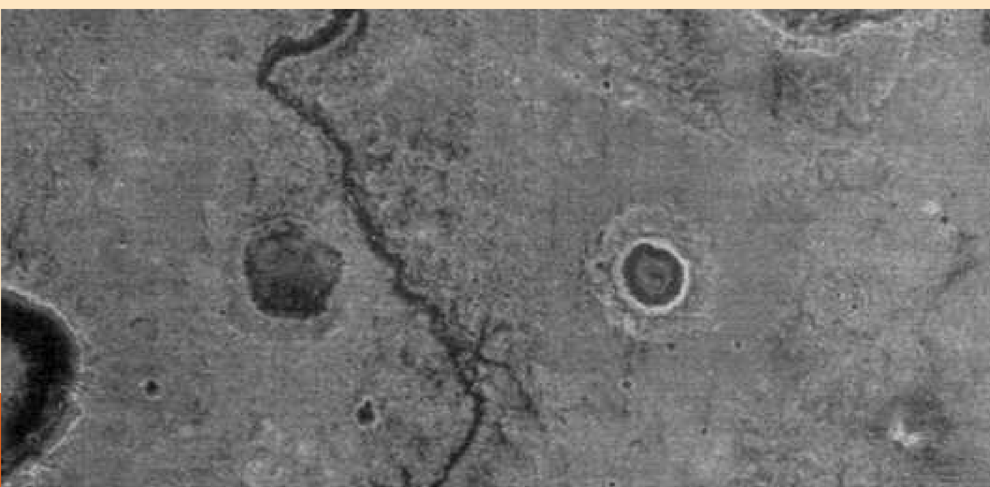
The Return of MARIE

On March 13, the Martian Radiation Environment Experiment (MARIE) instrument was coaxed into communicating once again. MARIE stopped working about four months after the spacecraft launched in April 2001. Designed to measure the radiation environment both on the way to Mars and at Mars in order to help plan for future human missions, MARIE did take data during the first months of *Odyssey*'s journey to Mars. Those data show a radiation environment with three times as many heavy ions as the International Space Station environment. Heavy ions are the most dangerous form of radiation for humans. With the instrument working once again, the radiation environment in Mars orbit can now be measured.

Water, Water Somewhere, Not a Liquid To Be Found

The main goals of the *Odyssey* mission revolve around water. By looking for minerals that often form in the presence of water, THEMIS searches for environments that may have once harbored liquid water. Through its thermal channel, THEMIS will be able to find active hydrothermal (hot) springs if they exist. The GRS instruments, meanwhile, will create an inventory of water-ice in the upper meter of the surface over the entire planet. Information from these instruments will help guide the future of Mars exploration while simultaneously giving us a better view of Mars, past and present.

Bruce Betts is director of projects at The Planetary Society.



This THEMIS nighttime thermal infrared image is basically a temperature map of the surface taken at night. Differences in temperature are largely due to differences in the abundance of rock, sand, and dust on the surface. Rock stays warm at night (brighter areas are warmer). By contrast, the sinuous channel floor is cold, suggesting it may be covered by material more fine grained than the surrounding plains. The presence of rock on the rim and inner wall and in the ejecta blanket indicates that this crater maintains some of its original character, despite erosion and deposition by Martian winds. Nighttime infrared images such as this one will greatly aid in mapping the physical properties of Mars' surface.
Images: NASA/JPL/Arizona State University

The Rampant Volcanoes of Io

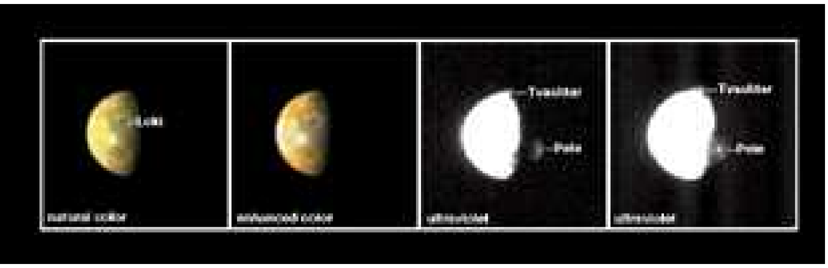
by Rosaly Lopes

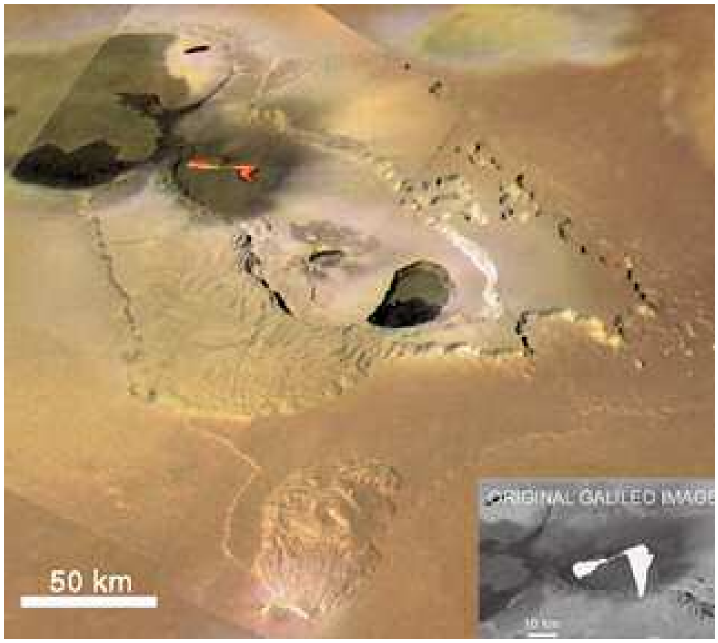
Jupiter's moon Io is a remarkable world. It is the most volcanically active body in the solar system, and its surface is the most colorful yet seen on a planet. Its vivid red, yellow, white, black, and, in some places, green surface earned it the nickname "Pizza Moon" back in 1979 when the first images of Io were returned by the *Voyager* spacecraft. Two decades later, we were able to fly the *Galileo* spacecraft close to the volcanoes of Io and obtain the first high-resolution visible and infrared images of this strange moon.

Flying close to Io is a risky business. Jupiter's powerful magnetic field creates a hostile, high-radiation environment—some 4 Megarads per day, or about 4,000 times the lethal dose for a human. This is not healthy for spacecraft either, and *Galileo* has suffered some problems due to radiation—luckily, nothing fatal. The spacecraft was designed to withstand a single flyby of Io, which took place in 1995 as *Galileo* came into orbit around Jupiter. Unfortunately, a problem with the spacecraft's onboard tape recorder prevented us from recording images of that encounter.

During the next four years, we kept *Galileo* at a safe distance from Io and acquired a wealth of data on Jupiter and its satellites, including Io. However, the lure of the volcanoes on Io was hard to resist, and in October 1999, we obtained our first images of the moon itself. *Galileo* survived, and we flew by Io again in November 1999 and February 2000. *Galileo* proved so resilient that three additional flybys were planned. The first of these was to take place on August 6, 2001, marking *Galileo*'s 31st orbit around Jupiter, designated I31 (*I* for Io).

While planning the observations for I31, we became aware of a risk other than radiation. The spacecraft's trajectory would take it right through a volcanic plume discovered a few months earlier when the *Cassini* spacecraft imaged Io on its way to Saturn. The volcano, called Tvashtar, was already known to us. It had erupted so spectacularly during *Galileo*'s third Io flyby in November 1999 that its brightness saturated part of the camera and spectrometer images.





Above: On its journey to Saturn, the* Cassini *spacecraft captured pictures of Io, revealing two active volcanoes erupting gigantic plumes of gas and dust. Pele, the plume visible near Io's equator, has been active for at least four years. Tvashtar, the other visible plume, had never been seen before the* Cassini *flyby. Tvashtar's plume reaches heights of nearly 400 kilometers (250 miles) above the surface. The bright spot over Pele's vent, seen in the far right image, remains a mystery. Although Pele's hot spot has a very high temperature, scientists believe the lava cannot be hot enough to show as a bright spot in an ultraviolet image.

Right: On November 25, 1999,* Galileo *took a close look at Tvashtar Catena, a chain of calderas on Io, just in time to capture a volcanic eruption. This mosaic combines low-resolution color images with higher-resolution black-and-white images. When the original image (inset) was taken, the hot molten lava was so bright, it saturated, or overexposed, the spacecraft's camera. The overexposed areas were color enhanced by* Galileo *scientists, based on their knowledge of how the camera behaves when saturated. In the enhanced image, the red areas are thought to be the most recent flows.

Left:* Galileo *captured this dramatic view of Io in September 1997 from a distance of 500,000 kilometers (about 310,000 miles). *Images: JPL/NASA*

Cassini's showing of a plume about 400 kilometers (250 miles) high erupting from Tvashtar in December 2000 indicated the eruption was long lived, as many on Io appear to be. As we prepared for the August 2001 flyby, we asked ourselves: will Tvashtar still have an active plume and, if so, will the spacecraft survive this close encounter?

Plumes and Hot Spots

Volcanic eruptions are hard to predict, even on Earth, where we have historical records of volcanic activity and an arsenal of monitoring instruments. Volcanoes were discovered on Io in 1979—before that, no active volcanoes outside Earth were known to exist. *Voyager*'s flyby of Io revealed the volcanoes in the form of plumes reaching up to 300 kilometers (185 miles) above the surface and "hot spots" detected in the infrared. (Hot spots are regions where the surface is hotter than its surroundings and, as we later learned, are sites of active lavas erupting on the surface. The designation *hot spot* stuck and is now used to describe an active volcano on Io.)

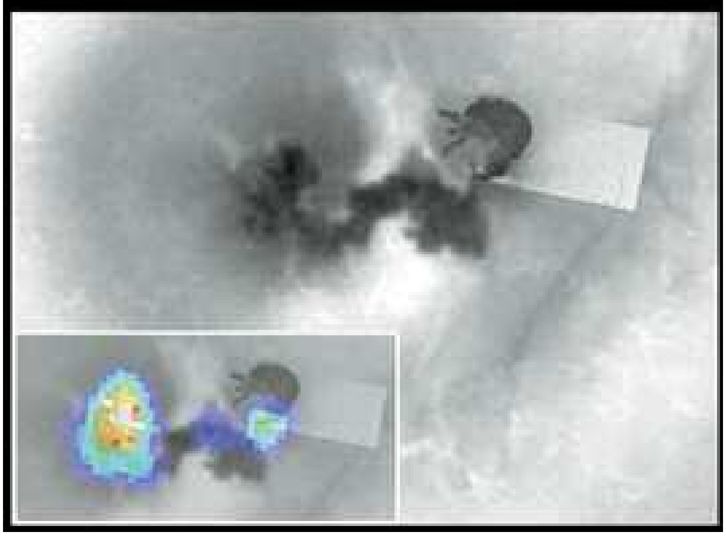
As August 2001 drew near, we concluded that the Tvashtar volcano would probably still be a hot spot, meaning there would be either active or cooling lava flows. What we had to assess was the likelihood of Tvashtar's having an active plume at the time of the *Galileo* flyby and, if it did, the chances of the spacecraft's surviving the event. There are more than 100 known hot spots on Io, but most don't show volcanic plumes. The plumes we have observed are made up mostly of sulfur dioxide and sulfur gases and particles. The main danger to spacecraft flying through a plume comes from particles that could damage vital systems. According to a theory developed by volcanologist Susan Kieffer, who has pioneered studies of the thermodynamics of Io's plumes, particles could be concentrated in bands due to standing shock waves in the plume structures.

The first plumes observed by *Voyager* were those from the Pele and Loki volcanoes. Linda Morabito, then a navigation engineer at the Jet Propulsion Laboratory, noticed an umbrella-shaped plume on the limb of Io while examining a *Voyager* image taken to help navigate the spacecraft (see sidebar, page 9). This plume was later named Pele, after the Hawaiian goddess of volcanoes. Closer inspection of the image showed a second plume, later named Loki.

Additional images led to the discovery of more plumes, and *Voyager*'s infrared instrument detected sulfur dioxide gas from the plume over Loki. The observations of Io's plumes resumed in 1996, when *Galileo* started monitoring Io's volcanoes. New active plumes and plume deposits were found, and it became clear that plumes play a major role in changing the appearance of the moon's surface. Plume deposits are sometimes dark gray, sometimes white to yellow, sometimes red, depending on whether the plume contains significant amounts of ash and magma fragments versus sulfur and sulfur dioxide. The vivid red colors that make Io's surface unique are due to short-chain sulfur (S_3 and S_4), which, after a few years on the surface, changes to the most stable form, S_8, showing as pale yellow. Seeing red on Io therefore means seeing an active or recently active volcano.

Volcanoes That Move?

Observations courtesy of *Galileo*, as well as of *Voyager* and the Hubble Space Telescope (which can, under some circumstances, detect plumes from Io), have helped us understand the different plume types. The *Galileo* flybys of Io allowed us to observe the eruption mechanism of the Prometheus plume. This plume, rising to a height of about



Above:* Galileo*'s camera peered down on Io's Prometheus volcano and compiled images to create this high-resolution mosaic. Scientists combined the mosaic with Near-Infrared Mapping Spectrometer (NIMS) data. The inset (lower left) is the same mosaic with NIMS temperature data superimposed. It appears that the lava is stored in an underground chamber beneath the caldera (the dark, bean-shaped feature at top right). About 15 kilometers (10 miles) south of the caldera, the lava reaches the surface (the smaller, colored spot in the NIMS image). From the volcanic vent, the lava travels almost 100 kilometers (60 miles) through lava tubes to the front of the flow.

Right:* A red ring, probably of sulfur, surrounding Io's Pele volcano dominates this image, taken by Galileo*'s camera in October 1999. The ring, deposited by Pele's gigantic plume, extends more than 1,400 kilometers (870 miles) in diameter. In this image, Io's surface is shown in approximate true color. The dark area inside the ring is the active volcano.
Images: JPL/NASA

100 kilometers (60 miles), was first discovered by *Voyager* in 1979. In the four months between the *Voyager 1* and *2* flybys of Io, the plume and its white donut-shaped deposit did not appear to change. *Voyager* failed to detect a hot spot at Prometheus, most likely because of the poor resolution of the spacecraft's infrared instruments over that area.

An explanation involving a "cold" plume at Prometheus was discarded when we examined the first distant observation of Io obtained by *Galileo*'s Near-Infrared Mapping Spectrometer (NIMS) in 1996, during the spacecraft's first orbit around Jupiter. Prometheus had a bright hot spot, indicating it was indeed an active, hot volcano. An observation returned by *Galileo*'s camera (Solid State Imaging system, or SSI) from this same first orbit showed that Prometheus had disgorged a new dark lava flow since the *Voyager* encounters. Surface changes like new lava flows are expected on active volcanoes. What nobody expected was that the Prometheus plume would have moved some 80 kilometers (50 miles) to the west since 1979, even though the size and appearance of the plume had not changed.

Volcanoes on Earth do not show such rapid movement (we can imagine the havoc they would create if they did). So, the Prometheus movement remained a puzzle—at least until October 1999, when *Galileo* flew close to Io and obtained visible and infrared images of Io's surface. The visible image showed a caldera located just to the north of the site from where *Voyager* had observed the erupting plume, indicating the new lava flow came from the caldera and had moved. The NIMS image showed not only that the entire lava flow was hot but also that the hottest region was near the *Voyager* plume site. We concluded that the plume, not the volcano, had moved. The volcano's vent, from which the flow erupted, was still located near the old plume site.

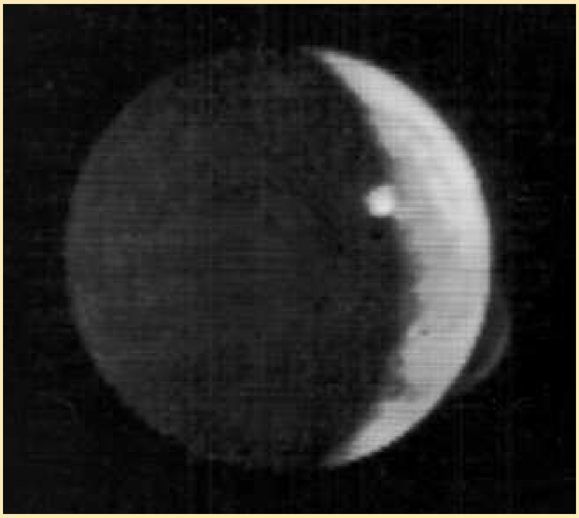
How did the plume move? Susan Kieffer proposed that the plume was being produced by the interaction of hot lava from the flow and the underlying sulfur dioxide snowfield. Although this process has not been observed on Earth, it is similar to what happens when terrestrial lava flows move over marshy ground, causing explosions as the water flashes to steam. Small "rootless" craters are created; many of these are found in Iceland, thanks to the combination of frequent eruptions and marshy swamps near Iceland's volcanoes. Kieffer's rootless plume model can explain other plumes on Io that appear to be linked to lava flows. For example, the Maui plume, active during *Voyager*, has since shut off. High-resolution coverage of the Maui region by NIMS showed that the lava flow that probably once fed the plume is no longer hot. Once the lava flow stopped and cooled down, the plume shut off.

Prometheus-type plumes can remain active for a long time, as Prometheus itself has shown. (We call it the "Old Faithful" of Io.) However, other plumes on Io have been seen to start and stop. Io expert Alfred McEwen has distinguished several types of plumes on Io from *Voyager* and *Galileo* data. At one extreme is the steady, sulfur dioxide–rich, Prometheus-type plume, which is less than 100 kilometers (60 miles) high. At the other is the Pele-type plume, which is intermittent, has significant quantities of sulfur as well as sulfur dioxide, and can reach heights of 300 kilometers (nearly 200 miles) or more. Also, the Pele-type deposits on the surface are larger and more spectacular than those of the Prometheus type. The best example is Pele itself: its red ring deposit is about 1,400 kilometers (870 miles) in diameter.

A Closer Look

The Tvashtar volcano has a plume deposit comparable to Pele's. The images of Tvashtar obtained by *Cassini* in December 2000 showed a giant red ring deposit very similar to that of Pele. Also, the height of the plume was about 385 kilometers (240 miles), similar to the height observed for the Pele plume. From these indications, we concluded that Tvashtar was the site of an intermittent Pele-type plume that might—or might

A Marvelous Discovery



Our first glimpse of a volcano on Io. Image: JPL/NASA

On March 5, 1979, *Voyager 1* arrived at Jupiter for a close-up look at the gas giant and many of its mysterious moons. At the Jet Propulsion Laboratory (JPL) just four days after the first spectacular images were returned, an astounding discovery was made: the first known active extraterrestrial volcanism in the solar system.

It was *Voyager* navigation team member Linda Morabito who first noticed peculiar bright marks near Io as she analyzed images from *Voyager*'s Optical Navigation Image Processing System (ONIPS). Initially, Linda thought there was another satellite behind Io. But, after studying trajectory data, she was convinced no other satellite could be anywhere near Io. She called on the expertise of her team leader, Steve Synnott, and the two checked and rechecked the data, but the bright crescent remained a mystery.

Linda believed she was on the verge of a discovery, perhaps a very important one. Her excitement was not shared by all, however, and she found herself having to persuade her colleagues to investigate the image further. After what she describes as "sparring" with a senior staff member, other experts were called in, including *Voyager* mission representative Stewart A. Collins, as well as Peter Kupferman, an expert on *Voyager*'s Vidicon camera. Huddled around Linda's computer, the group came up with three possible explanations for the strange bright light: (1) a newly discovered satellite of Jupiter, (2) a newly discovered satellite of Io, and (3) an Io-based phenomenon.

Linda and her colleagues examined latitude and longitude parameters and noticed that the anomaly matched a known heart-shaped volcanic feature on Io. The correlation suggested the mysterious light could be a volcanic cloud, but such a scenario seemed almost impossible as the anomaly was roughly 0.15 the radius of Io and about 270 kilometers (170 miles) above the surface. If this was a volcanic cloud, it was a huge one!

After learning of the anomaly, *Voyager* project scientist Ed Stone commanded the spacecraft to look for traces of what might be a volcanic cloud. He said to Linda, "If it is verified, it will be a marvelous discovery."

Two days later, Linda received a call from the science imaging team: "There are volcanoes all over the place. You'd better get up here." Elated, Linda yelled back to the navigation team, "It's verified!" A cheer broke out.

That first ONIPS image (above) revealed simultaneous eruptions. The bright crescent on Io's limb (lower right) is the gigantic plume that was later named Pele. The bright mark on the terminator (the shadow between day and night) is Loki's volcanic cloud reflecting the rays of the rising Sun.

Linda Morabito, now Linda Morabito Kelly, left JPL in 1981 to raise a family. In 1997, Linda turned her attention to The Planetary Society, where she is currently manager of program development.

—Jennifer Vaughn, Managing Editor

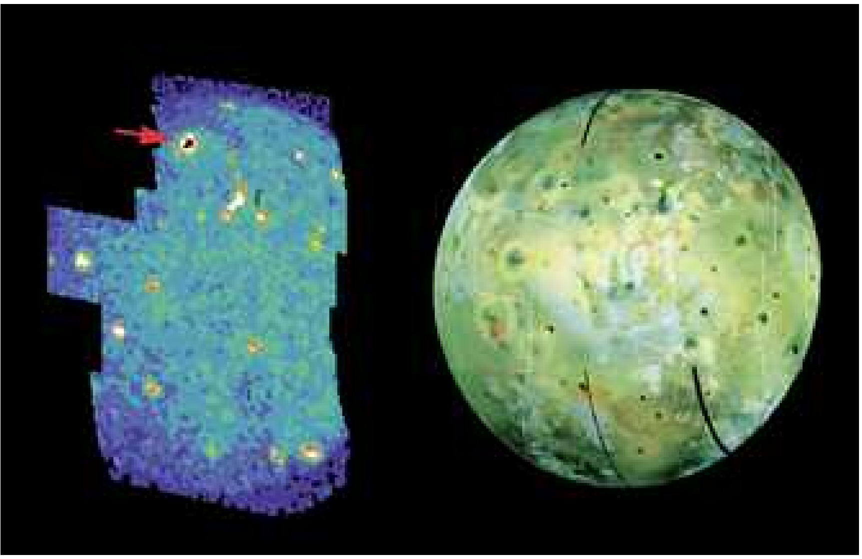
not—be active at the time of the *Galileo* flyby.

After a lot of discussion, we decided that *Galileo* could survive a flight through the active plume. We based our decision mostly on the likelihood of low particle density in the plume. However, we realized the encounter would not be without risk. In fact, the risk from cumulative radiation was considerable—*Galileo* had already received about three times the dose of radiation it had been designed to withstand. As Torrence Johnson, our project scientist, once said, *Galileo* had gone way beyond its warranty.

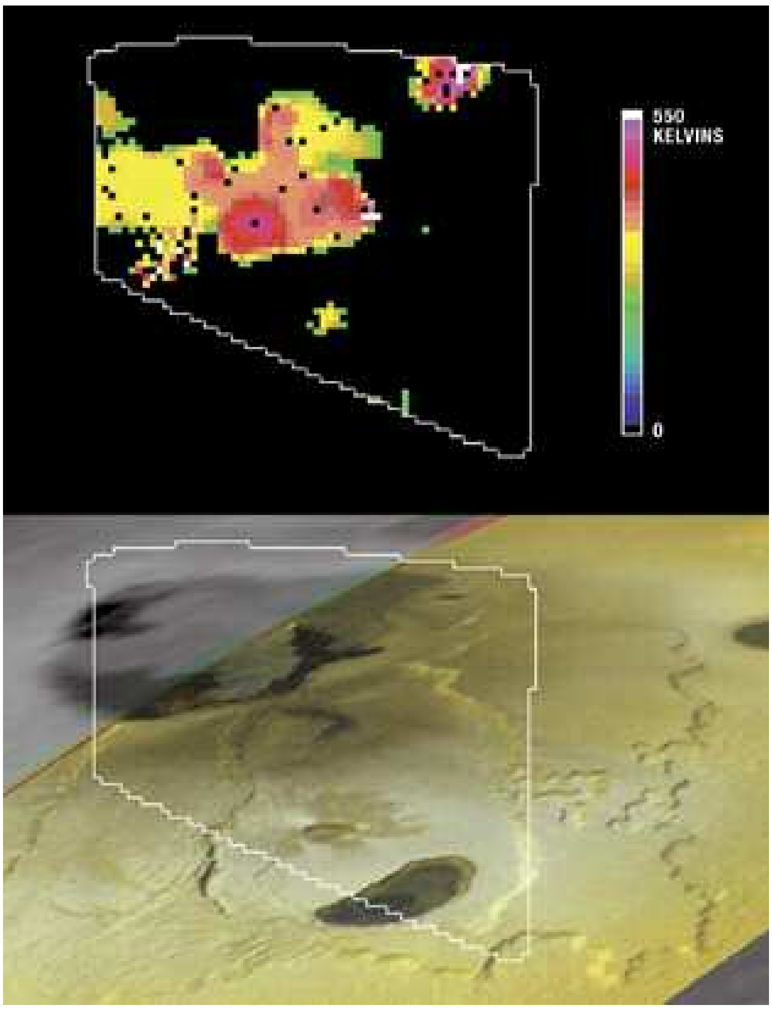
When the flyby over Io's north pole took place on August 6, 2001, *Galileo* came through just fine. We did not know at first if the Tvashtar plume had been active or not, as images stored on the onboard tape recorder are transmitted slowly to Earth.

Once the camera's images were analyzed, a plume was clearly seen. However, its location did not match Tvashtar's. As camera team members tried to pinpoint where the plume was erupting, an infrared image from NIMS covering a large area of Io, pole to pole, showed a new, very bright hot spot located about 600 kilometers (370 miles) to the southwest of Tvashtar. This was clearly where the plume originated. The new volcano, which is yet unnamed, was going through a gigantic eruption. Its plume was 500 kilometers (310 miles) high, the tallest ever seen on Io. *Galileo* was, for the first time, able to take a "whiff" of a plume. A plasma science experiment led by Louis Frank detected sulfur dioxide molecules within minutes of their escaping from the plume vent. Commenting on the results, Frank was quoted as saying, "*Galileo* smelled the volcano's strong breath and survived."

Meanwhile, infrared images returned by NIMS indicated that Tvashtar was still active, as hot lavas could be detected



Volcanic hot spots pepper this Near-Infrared Mapping Spectrometer (NIMS) infrared color-coded image of Io (left). The arrow points to a newly discovered hot spot in Io's high northern latitudes.* Galileo *had detected a new plume, but it took this NIMS image to pinpoint exactly where the plume was erupting. The bright regions (yellow to red to white) in the NIMS image are all volcanic hot spots. Io has a total of 108 known hot spots. The visible-light image at right, taken by* Galileo*'s camera, shows the same face of Io, for context. *Image: JPL/NASA*



In August 2001,* Galileo*'s Near-Infrared Mapping Spectrometer revealed new and older lava flows in Io's Tvashtar region (top). The multiple hot spots indicate continuing shifts in the location of Tvashtar's eruptions since the region's volcanic activity was first noticed in December 1999. Each pixel represents an area of about 2 kilometers (1 mile). The bottom context image, taken in February 2000 by* Galileo*'s camera, shows the volcano's clear, bowl-like depression. *Image: JPL/NASA*

on the surface. The magnetometer on *Galileo* showed a correlation between several volcanoes, including Tvashtar, and the signature of electrical currents flowing along magnetic field lines. The principal investigator for the instrument, Margaret Kivelson, explained the correlation in terms of material, shot high by volcanic plumes, affecting conductivity more than 100 kilometers (60 miles) above the surface. She pinpointed the Tvashtar area as a plume site. If the plume were indeed active but made up mostly of gas with very few particles, it would have been a "stealth-type" plume, which, as the name implies, is extremely difficult to detect using a camera.

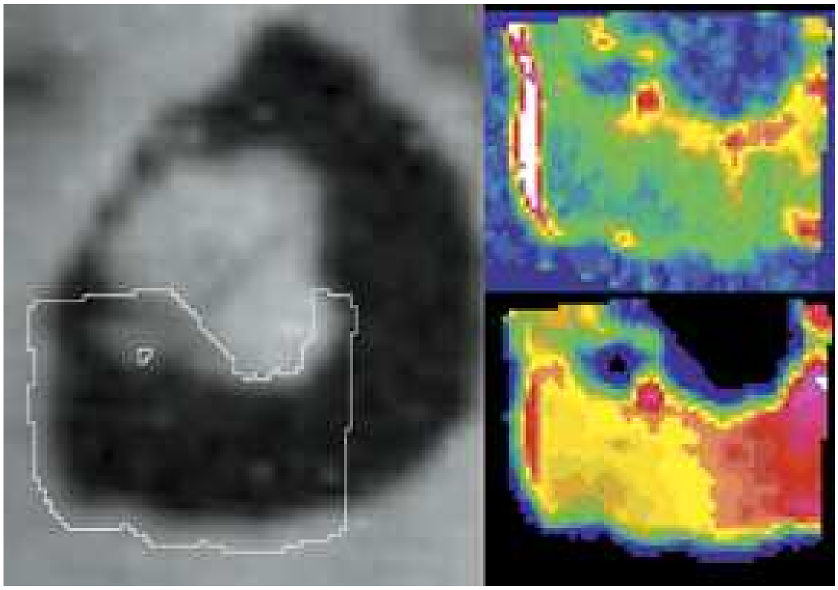
Polar Flybys

Galileo flew in between Tvashtar and the new plume and survived. After a short orbit around Jupiter, the spacecraft made its sixth close pass of Io's surface, this time over the southern pole, on October 16, 2001. The reason for the two polar flybys was to determine whether Io has its own magnetic field. Previous results from equatorial flybys had proved inconclusive. As a bonus, the remote-sensing teams now had another opportunity to acquire images of Io's volcanoes never before seen at close range. We started receiving infrared (NIMS) observations a few weeks after the event, during the Thanksgiving holiday. I had no trouble choosing between hot turkey and hot Io.

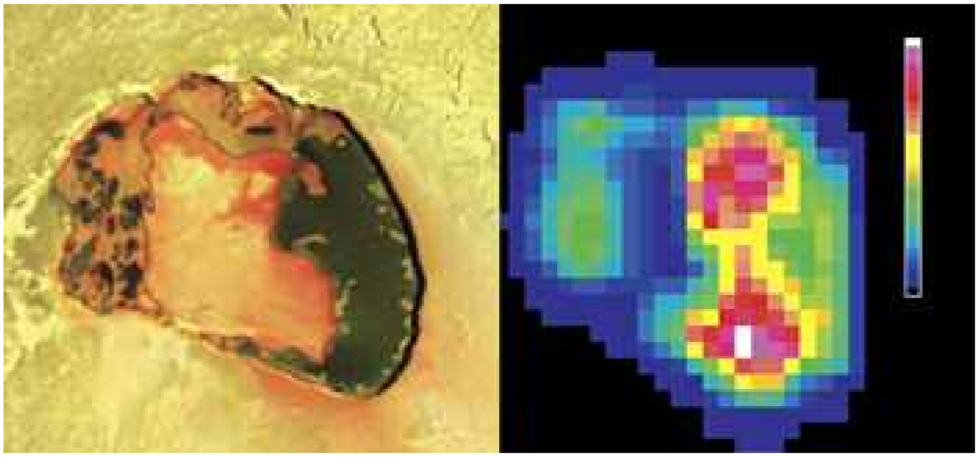
The first infrared image we received was of the Loki volcano. The solar system's most powerful volcano, Loki generates more energy than all the Earth's volcanoes combined. Loki is bright enough to be easily observed using telescopes on Earth, and monitoring since the *Voyager* days has shown that this volcano brightens and fades at intervals of a few months, indicating that new eruptions happen often.

Yet, despite many observations, there was still debate on the type of eruption taking place. The visible images showed that Loki has a giant caldera about 200 kilometers (125 miles) across—larger than Hawaii's Big Island. The caldera floor is covered by dark lava except for a portion in the middle that may be an island or ridge. Loki's eruptions could be outpourings of lava on the floor of the caldera so that each eruption deposits new lava on top of old, cooled flows. Or Loki could be a lava lake, perhaps similar to phenomena observed on Earth's volcanoes, such as Hawaii's Kilauea. In this scenario, the lake would be continuously active under a cooled crust; every now and then, the crust breaks and hot lava from underneath pours out, causing the brightening seen in infrared wavelengths.

Galileo flew over Loki while the volcano was in darkness—an ideal infrared observation because the effect of sunlight is not present and all the bright regions detected are due to heat. The distribution of heat in the caldera is consistent with the lava lake idea: the image at 2.5 microns shows that the brightest (and hottest) areas are found near the margins of the dark lava, where the lava comes into contact with the caldera wall and with the central island or ridge. The cooler crust of molten lava lakes on Earth, such as on Kilauea, tends to drift outward and hit against the



Right:* Galileo's *Near-Infrared Mapping Spectrometer (NIMS) observed high temperatures at Io's Loki volcano that may indicate freshly exposed material at the shore of a lava lake. Two NIMS temperature maps of the southern portion of Loki (right) show hot (lower right) and hotter (upper right) features. In the lower right image, the yellow-orange is correlated to temperatures of about 360 Kelvins (90 degrees Celsius, 190 Fahrenheit) and the reddish color to temperatures of about 430 Kelvins (160 degrees Celsius, 310 Fahrenheit). The upper-right image shows a white streak correlated to temperatures of roughly 840 Kelvins (570 degrees Celsius, 1,050 Fahrenheit). The context image (left), captured by* Galileo*'s camera, shows Loki's dark volcanic crater surrounding a light-colored island.



Below right: A thermal portrait (right) of Io's Tupan Caldera shows a relatively cool area at its center, which is possibly an island. In this NIMS image, reds and yellows indicate hotter regions, and blues are cold. The hottest regions in the NIMS image correspond to the dark portions in the visible-light image from* Galileo*'s camera (left). Scientists combined the NIMS and visible-light data and determined the dark areas are either active or cooling lava.

Images: JPL/NASA

caldera wall. This causes the crust next to the wall to break up, exposing hotter material from underneath.

Io may have many lava lakes. As *Galileo* flew over the surface during the October flyby, another volcano came into view. Tupan, named after the Brazilian god of thunder, is a volcanic caldera similar to Loki. However, it is smaller—roughly 75 kilometers (50 miles) across—about the same diameter as Yellowstone, the largest volcanic caldera on Earth. Tupan, like Loki, has a central cold area, which may be an island or ridge, surrounded by dark lava flows that are either active or cooling.

The big difference in *Galileo*'s observations of Loki and Tupan is that the spacecraft saw Tupan in the sunlit portion of Io's surface, allowing the camera to obtain a color image showing a surreal pattern of black, green, red, and yellow materials. The infrared image obtained by NIMS showed that the dark materials correspond to warm or hot areas, while the other areas are rich in sulfur dioxide. Data from the two sets suggest that Tupan is also a lava lake. The dark materials are therefore either active or cooling lava. The yellow materials and the diffuse red regions are sulfurous compounds, the diffuse red probably S_4 condensed from gases escaping from vents (a plume has not yet been observed at Tupan, but one may have been present in the recent past). The green materials, seen in small patches elsewhere on Io, are harder to explain. It has been noticed that green colors appear to form where red sulfur has interacted with dark lavas. The Tupan image has thus provided our best evidence so far that this type of chemical reaction is taking place on Io.

A Thwarted Goodbye

As *Galileo* receded from Io in October 2001, a global observation by NIMS showed many previously unknown hot spots—Io is indeed peppered with them. In January 2002, the *Galileo* team prepared for the last flyby of Io. Anticipation ran high. However, an anomaly, no doubt due to radiation, caused the spacecraft to go into "safe" mode just before the Io observations were acquired. Although the spacecraft team worked hard and implemented contingency plans, it was not possible to return *Galileo* to normal operation until after it had traveled past Io.

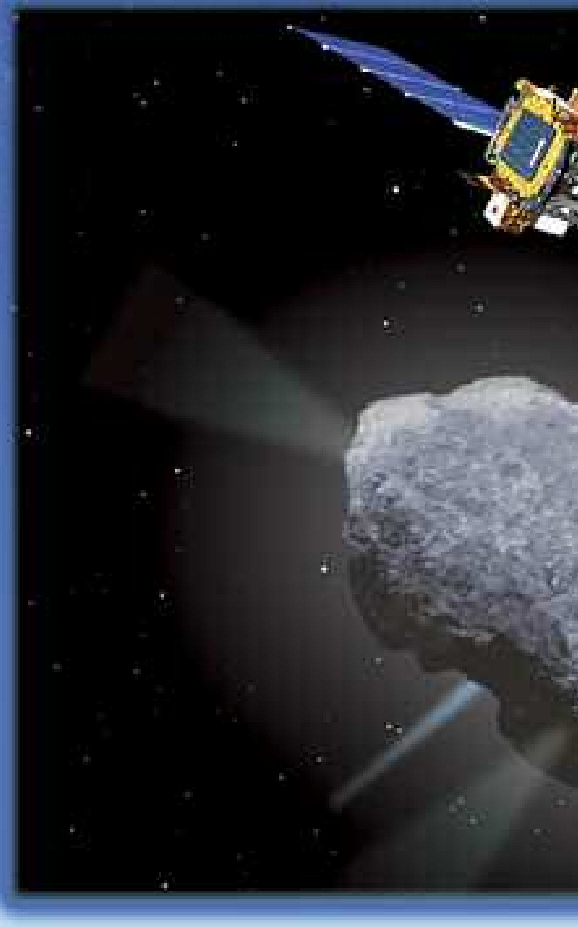
Disappointed as we were, we recognized that *Galileo* had already performed beyond all expectations. We acquired a wealth of data on Io from 1996 to 2001 and discovered some amazing facts about this strangest of moons.

Still, Io has eluded our scrutiny. For one thing, we never got a close look at Io's Jupiter-facing side. Clearly, there is much more to be learned from future missions to this immensely intriguing moon.

Rosaly Lopes is a member of Galileo*'s Near-Infrared Mapping Spectrometer Team at the Jet Propulsion Laboratory. An expert on planetary volcanism, she studied active volcanoes on Earth and Mars before turning her attention to the volcanologists' paradise of Io.*

Deep Space 1: The New M

Going deep into space demands new hardware, new software, and, above all, new ways to fly spacecraft. NASA's Deep Space 1 mission pioneered all three techniques—and opened a road to other worlds.



by Robert Burnham

The most advanced rocket engine in existence produces no roar of exploding propellants, no flame, no thunder. Instead, it emits a silent, eerie blue glow that pushes ever so gently—no harder, in fact, than a sheet of paper resting in your hand. This rocket engine, the heart of NASA's *Deep Space 1* probe, is an ion drive, and it represents spaceflight's future.

Ion drives were tested in Earth orbit during the 1960s and '70s. But a spaceflight in deep space wasn't attempted until 1998, when NASA launched *Deep Space 1* (*DS1*), the first mission in its New Millennium program. *DS1*'s flight plan called for a trip to an asteroid, followed by a possible visit to two comets.

Because New Millennium projects test advanced technologies, *DS1*'s mission put science in the backseat as it tried out a dozen hardware and software innovations. New Millennium's goal is to reduce costs by making spacecraft smaller and smarter.

Managed by the Jet Propulsion Laboratory (JPL), *Deep Space 1* was launched October 24, 1998 on a chemically fueled Delta II rocket from Cape Canaveral, Florida. Launch required chemical fuel because ion drives can't provide the high accelerations necessary to lift from a planet's surface. Once free of Earth, however, *DS1* unfolded its solar panels, lit the ion drive, and set off toward a July 1999 meeting with an asteroid known as 9969 Braille.

A New Kind of Spacecraft

Deep Space 1 used an uncommon approach. Instead of testing elements piecemeal on conventional flights, the entire *DS1* spacecraft was built around new technologies. This meant the most important components had to work right from launch. For example, while *DS1* carried ordinary hydrazine thrusters for quick maneuvering, their fuel supply was limited. Most of the mission's pushing and shoving was done with the ion drive. It ran on xenon gas, commonly used in photo flash tubes. An electrode in the engine ionized the xenon, giving it an electrical charge. At the rear, two metal grids, charged positive and negative, exerted a powerful electrostatic pull on the ionized gas. The force shot xenon ions through the grid and out the back of the engine at more than 27 kilometers (17 miles) per second.

"The ion drive worked just beautifully," says project manager Marc Rayman of JPL. "It's ideal for missions where you don't need high acceleration."

Over the mission's course, Rayman says, the ion engine fired perfectly for 670 days' total running time and yielded enough thrust to change the spacecraft's velocity by 4.2 kilometers (2.6 miles) per second. The drive exerted a steady, gentle push, running for weeks on end. It was steerable and could thus alter *DS1*'s trajectory without the hydrazine thrusters. The drive's "mileage" was great, too: in one six-week run, the engine con-

Millennium in Spaceflight

In September 1999, just shy of a year after it left Earth, Deep Space 1 *(*DS1*) completed its primary mission to test cutting-edge space technologies. With a successful primary mission under its belt, NASA saw an opportunity to extend* DS1*'s mission two more years, sending the spacecraft on a risky rendezvous with a comet. In September 2001,* DS1 *flew daringly close to comet Borrelly, returning the best-ever images of a comet to date.* *Illustration: JPL/NASA*

sumed less than 5 kilograms (11 pounds) of xenon.

The ion drive depended on electric power from the solar panels. As another technology test, these incorporated high-efficiency solar cells with 720 lenses to concentrate sunlight. They yielded 15 to 20 percent more power than conventional panels.

DS1 kept on course using AutoNav, its automated navigation system. AutoNav took images using the Miniature Integrated Camera and Spectrometer (MICAS) and identified stars and planets in the field of view. From these images (plus a commercial star tracker), AutoNav computed the spacecraft's whereabouts in the solar system, steering while the ion engine was firing and controlling its operations.

MICAS, one of two science instruments aboard, combined a CCD camera, an advanced active pixel sensor camera, and ultraviolet and infrared spectrometers. (Unfortunately, the UV spectrometer failed soon after launch.) The other science instrument was the Plasma Experiment for Planetary Exploration (PEPE). It measured charged particles (electrons and ions) in the solar wind, plus any emitted by a comet or asteroid that could provide clues to its composition. PEPE could also detect magnetic fields.

The spacecraft reported its general health to the Deep Space Network on Earth by the Beacon Monitor, which broadcast one of four tone signals. These had meanings ranging from "I'm fine" to "contact me ASAP." More complex was the Remote Agent software. Ground control told this onboard mission manager in general terms what to do, and it proceeded to coordinate spacecraft systems, programming their operation.

The rest of *DS1*'s tests involved miniaturized electronics and structural elements integrating spacecraft systems. Common themes dominated: low mass, low power, high autonomy, and high reliability.

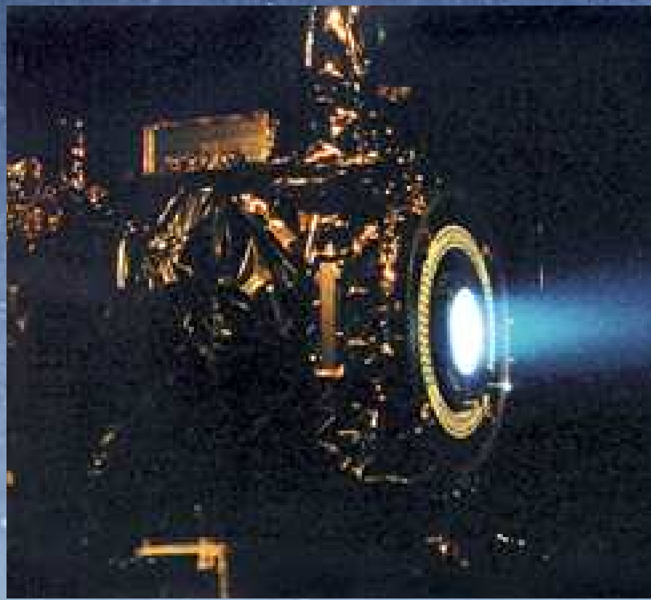
Blindman's Asteroid

By early summer 1999, *DS1* had passed almost all its tests and was nearing asteroid Braille, formerly known as 1992 KD. The asteroid was renamed just before the flyby to honor Louis Braille, the blind French educator, following a contest sponsored by The Planetary Society (see sidebar, page 15).

Little was known about asteroid Braille. Ground-based studies showed it was a kilometer or two across and elongated; its day lasted 9.4 Earth days. The spectrum of its surface hinted that Braille resembled the larger basalt-covered asteroid 4 Vesta. When *DS1* encountered Braille on July 29, 1999, the asteroid was overtaking the spacecraft at 15.5 kilometers (9.6 miles) per second and rising through *DS1*'s orbital plane.

As Braille approached, AutoNav snapped images using the MICAS CCD camera but couldn't quite locate the asteroid. Analysis of the images by mission control

Herman Mikuz captured this ground-based, false-color CCD image of comet Borrelly on January 7, 2002 from the Crni Vrh Observatory in Slovenia. Mikuz is a 2001 Planetary Society Shoemaker NEO Grant winner.
Image: Herman Mikuz



Above: This photograph of a xenon ion engine—captured through a port of the vacuum chamber where it was being tested at NASA's Jet Propulsion Laboratory—shows the faint blue glow of charged atoms being emitted from the engine.
Photo: JPL/NASA

Right: DS1 is lifted off its work platform, giving us a good look at the ion propulsion engine—the first nonchemical propulsion system serving as the primary means to propel a spacecraft. Above the engine are two of the spacecraft's solar wings, folded and ready for launch.
Photo: KSC/NASA

Deep Space 1 Resources

Online

Deep Space 1's home page
nmp.jpl.nasa.gov/ds1/index.html
New Millennium Program
nmp.jpl.nasa.gov/index_non.html (non-Flash browsers)
nmp.jpl.nasa.gov (requires Flash)
The Planetary Society contest to name 9969 Braille
planetary.org/news/contest-ds1.html
Dawn mission to asteroids Ceres and Vesta
www-ssc.igpp.ucla.edu/dawn
www.college.ucla.edu/dawn

In Print

Burnham, Robert. 2000. *Great Comets*. Cambridge, UK; Cambridge University Press.

Peebles, Curtis. 2000. *Asteroids: A History*. Washington, D.C.; Smithsonian Institution Press.

found Braille in several, but it was 400 kilometers (250 miles) from its presumed position and fainter than expected. Informed of Braille's correct location, AutoNav altered course. But shortly afterward—and just 16 hours before closest approach—AutoNav's software hit a bug that forced the spacecraft into safe mode. *DS1* turned away from Braille, oriented on the Sun, and waited for instructions from Earth.

"That was very discouraging," says Rayman. "I initially thought this is just over. Maybe we shouldn't even try to recover it. But getting *DS1* back was one of the team's best moments."

JPL mission controllers scrambled to refocus the spacecraft on the fast-approaching asteroid. They reprogrammed AutoNav with just four minutes to spare. But *DS1*'s new course was not as accurate, so it missed Braille by 28 kilometers (17 miles) instead of the planned 15 kilometers (9 miles).

Then, just minutes before closest approach, AutoNav switched, as planned, to the active pixel sensor, believed more effective with large or bright objects. However, this

Renaming That Rock

In 1999, The Planetary Society contributed to the Deep Space 1 mission by sponsoring a contest to give a permanent name to the spacecraft's first target, asteroid 1992 KD.

The asteroid was discovered May 27, 1992 by Eleanor Helin and Ken Lawrence from Palomar Observatory during the NASA-funded Planet-Crossing Asteroid Survey. Its orbit ranges from inside that of Mars out into the main asteroid belt, taking 3.6 years for one circuit.

Out of several hundred names proposed, codiscoverer Helin chose 9969 Braille, proposed by Kerry Babcock of Port Orange, Florida, a software engineer at NASA's Kennedy Space Center. The name honors Louis Braille (1809–1852), the blind French educator who developed the system of printing and writing named for him. The number 9969 in the asteroid's formal name indicates it is the 9,969th asteroid to be numbered since the first asteroid, Ceres, was discovered in 1801. —RB

Above: In July 1999, DS1 *approached asteroid 9969 Braille at an approximate distance of 15 kilometers (9 miles). However, a problem with* DS1*'s target-pointing software prevented the spacecraft from capturing any close-up images of the asteroid. This image of Braille was created from a composite of two MICAS images taken 914 seconds and 932 seconds, respectively, after* DS1*'s closest approach.* *Image: JPL/NASA*

camera's lower sensitivity meant that AutoNav lost track of Braille. Result: no detailed images.

After closest approach, *DS1* finally spotted Braille and took two long-distance images as the asteroid receded. These showed Braille to be 2.2 by 1.0 kilometers (1.4 by 0.6 miles) in size and irregular, but they revealed little more. Spacecraft systems worked well during the flyby, but the loss of close-up images disappointed many. The infrared spectrometer and PEPE, however, got some data. PEPE detected no magnetic field and no particles coming from Braille, as expected, while the spectrometer results suggested a surface like Vesta's or else like that of ordinary chondrite meteorites.

"It's unfortunate we didn't get close-up images of Braille," says Robert Nelson of JPL, the mission's project scientist. "But NASA had directed us to use the flyby to test *DS1*'s technology. Science was secondary.

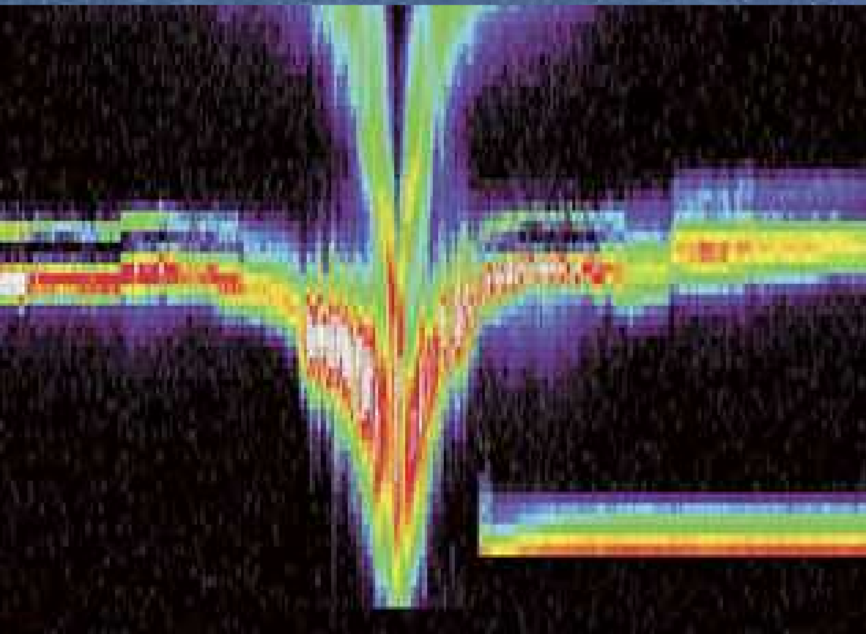
"And the encounter showed that while NASA had been reluctant to try some technologies because they were new, in fact, they were ready for deep-space missions."

Off to a Comet

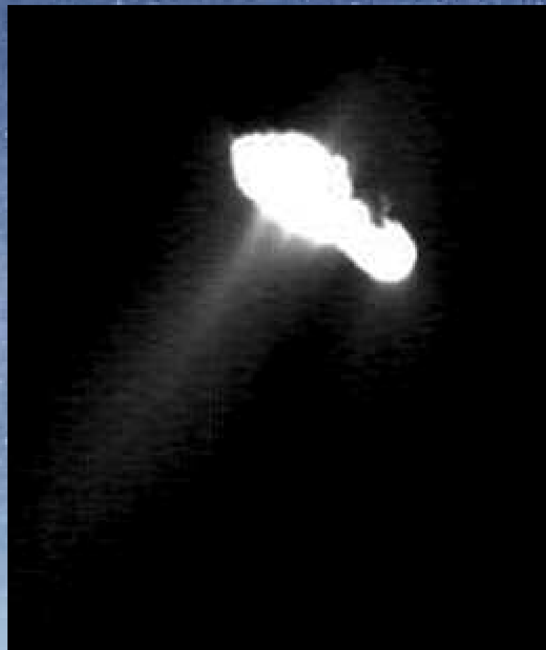
The Braille flyby ended *DS1*'s primary mission. But flight planners had scripted an extended flight with visits to two periodic comets, 107P/Wilson-Harrington and 19P/Borrelly. The extension would also change *DS1*'s focus from technology testing to scientific exploration. NASA gave the nod, and the ion drive began firing to take *DS1* to comet Wilson-Harrington, a curious object that has appeared both cometary and asteroidal. Flyby was set for January 2001.

Then, in November 1999, *DS1*'s star tracker abruptly failed. It had been informing the spacecraft of *DS1*'s orientation and was essential for maintaining contact with Earth and for flying to any target. The failure brought mission controllers again to the verge of calling it quits.

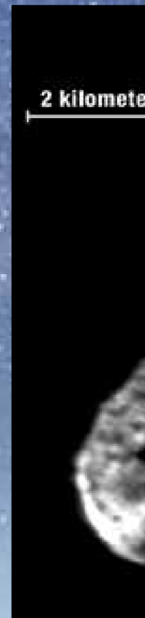
But engineers turned MICAS into a star tracker, despite its tiny field of view. And they operated *DS1* manually, since AutoNav required the original star tracker to work. (Ironically, the tracker was old technology, an off-the-shelf item.) By the time mission controllers learned to fly the spacecraft all over again, however, seven



One of **DS1**'s two science instruments was designed to measure the charged particles in the solar wind. The Plasma Experiment for Planetary Exploration discovered that a very strong interaction occurs between the solar wind (the horizontal red bands to the left and right) and Borrelly's coma. This image is made up of more than 1,300 energy spectra captured on September 22, 2001. At this point, **DS1** detected that the solar wind picked up charged water particles from Borrelly's coma (upper green band near center), slowing the wind sharply and creating the V-shaped energy structure at center. Image: NASA/University of Michigan



This **DS1** image, taken on September 22, 2001, has been enhanced to reveal dust being ejected from the nucleus of comet Borrelly. As a result, the nucleus, which is about 8 kilometers (5 miles) long, is bright white in the image. The main dust jet is directed toward the bottom left of the frame. Another, smaller jet feature is seen at the tip of the nucleus on the lower right-hand limb. The terminator, or the demarcation between day and night, on the comet is visible toward the upper right. This representation shows a faint ring of brightness separated from the terminator by a dark, unlit area. This is possibly a crater rim, seen in grazing illumination, which is just about to cross into darkness as the comet rotates.
Image: JPL/NASA



Mission Basics

Cost: $152.3 million (FY1995–01)

Launched: October 24, 1998 from Cape Canaveral, Florida on a Delta II rocket

Spacecraft details: 486 kilograms (1,071 pounds); body measures 2.1 by 1.7 by 2.5 meters (6.9 by 5.6 by 8.2 feet); solar panels extend 11.8 meters (38.6 feet)

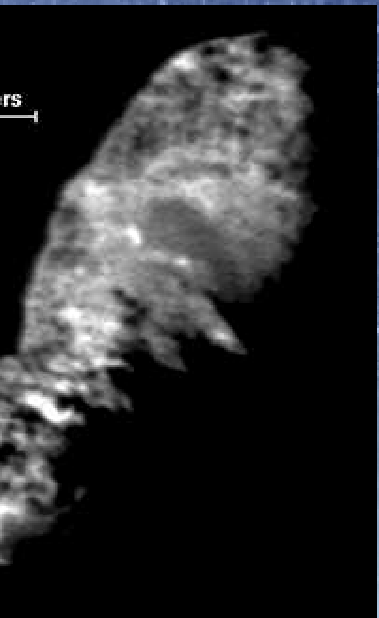
Science instruments: Miniature Integrated Camera and Spectrometer (MICAS), Plasma Experiment for Planetary Exploration (PEPE)

Technology tests: ion propulsion system, autonomous navigation and flight control software (AutoNav, Remote Agent, Beacon Monitor), solar concentrator power arrays, various deep-space electronics featuring low power and high onboard automation
—*RB*

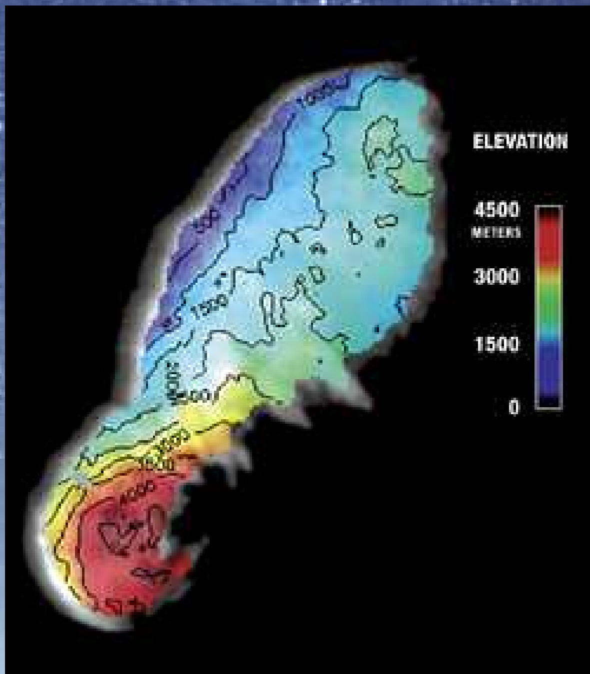
months had passed—too late for Wilson-Harrington. So, *DS1* aimed for comet Borrelly, an active comet with a 6.9-year period (and a 25-hour day) that comes just inside the orbit of Mars. The flyby was on September 22, 2001, eight days after the comet's closest approach to the Sun.

The encounter succeeded spectacularly. Flying past at 16.5 kilometers (10 miles) per second, *DS1*'s closest approach was 2,171 kilometers (1,349 miles). MICAS imaged the potato-shaped nucleus—some 8 kilometers (5 miles) by 4 kilometers (2.5 miles) in size—with a resolution of 48 meters, the sharpest images ever of a comet. PEPE found the nucleus off center within the comet's coma, perhaps from solar wind turbulence or activity on the nucleus. Coma components included water vapor, hydroxyl, nitrogen, and carbon.

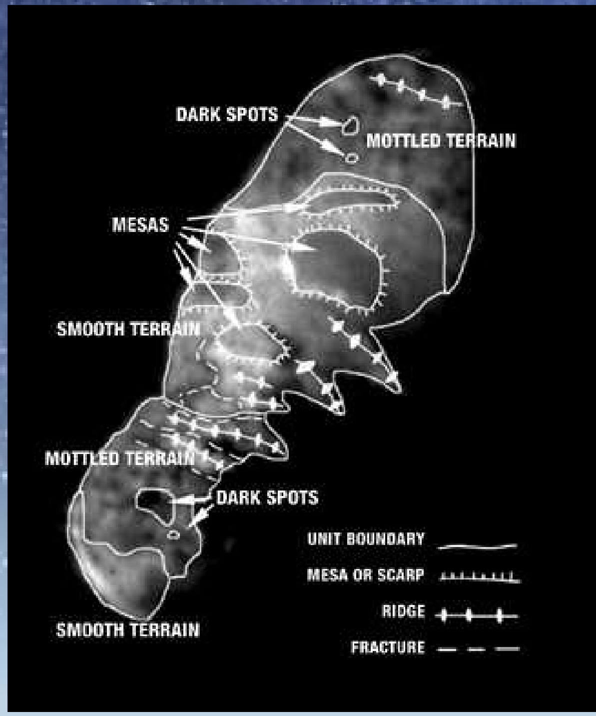
MICAS captured a surface that combined smooth terrain (with mesa-like features) in the center with rough, mottled terrain (with very dark spots) elsewhere. Borrelly's surface was as black as photocopy toner (some parts even blacker) and had peak temperatures of 72 degrees Celsius (162 degrees Fahrenheit). Stereo



This was the last image **DS1** captured on September 25, 2001, just seconds before its closest approach to the rocky nucleus of comet Borrelly. It is also the image showing the highest resolution (about 45 meters per pixel). Taken by the Miniature Integrated Camera and Spectrometer, the image reveals a variety of terrains and surface textures, mountains and fault structures, and darkened material on the nucleus' surface. At this point, the spacecraft was about 3,400 kilometers (2,000 miles) away from Borrelly's nucleus. Borrelly's width is represented by the 2-kilometer (1.2-mile) scale bar.
Image: JPL/NASA



This colored digital terrain model (DTM) of Borrelly's nucleus was constructed from a stereo pair of CCD images. Scientists expect the DTM to resolve features larger than 500 meters horizontally, with a vertical accuracy of about 150 meters. The height of the comet's surface features is represented by the colored scale bar at right.
Image: courtesy Juergen Oberst



DS1's images transformed Borrelly from an obscure astronomical body into a geologic object with striking surface morphology and processes. These images provide the best window so far into the surface structure, as well as geologic processes and history, of a comet. This morphological map, overlaid on the high-resolution image, delineates the assortment of geologic features on Borrelly's nucleus.
Map: courtesy Dan Britt

images mapped the surface in three dimensions.

Two narrow jets of dust shot upward from the smooth terrain. (Fainter diffuse jets were also visible.) The main jets, some 500 meters in diameter, reached about 5 kilometers (3 miles) altitude before losing their narrow shape. The jets, erupting close to Borrelly's rotation axis, were constantly in sunlight. Overall, about 10 percent of Borrelly's nucleus was active, and it produced 1/25th the gas and dust coming from comet Halley's nucleus.

"Since we're going to fly future missions close to comets—*CONTOUR*, *Deep Impact*, *Rosetta*—understanding the near-nucleus environment is essential," says Laurence Soderblom of the US Geological Survey, the MICAS team leader. "After Braille, our expectations were restrained. Yet, at Borrelly, everything we planned worked."

It's a Wrap

After Borrelly, *DS1*'s mission quickly wound down. It cruised while engineers finished final tests. Then, on December 18, 2001, mission controllers put *Deep Space 1* into hibernation, leaving its radio on. *DS1* now orbits the Sun every 1.56 years at an average distance of 201 million kilometers (125 million miles).

What are *DS1*'s lessons? One is that onboard automated navigation is feasible and powerful. Says Rayman, "We discovered how really valuable AutoNav was when we had to fly the spacecraft manually."

A more important finding is that ion drives have arrived, and that's great news for planetary exploration. Indeed, an ion engine has already been chosen for the *Dawn* spacecraft (due for launch in May 2006), which will explore the asteroids 4 Vesta and 1 Ceres.

DS1's ion engine drew power from solar panels, which are most effective inside the asteroid belt. *Dawn* and other future planetary missions can use them to explore the inner solar system. But fed by a nuclear power source, an ion drive can motor as deep into space as anyone cares to go. This means the road to Pluto, the Kuiper belt, or farther still lies wide open.

Robert Burnham is the author of the forthcoming constellation guide Exploring the Starry Sky*, to be published in 2002 by Cambridge University Press.*

World Watch

by Louis D. Friedman

Washington, DC—Under the fiscal year 2003 budget proposed by the Bush administration, NASA would receive a 13 percent increase for space science and initiate a new mission line called New Frontiers. The agency is also authorized to develop nuclear propulsion and power for deep-space missions. Nuclear propulsion will improve the performance of missions to the outer planets, and nuclear power will make possible long-lived landers and future outposts on Mars.

These potential advances are offset, however, by the cancellation of currently scheduled outer planets missions: funding was eliminated for both the *New Horizons* mission to Pluto and the Europa orbiter. Exploration of the outer planets will now be delayed by a matter of years, maybe even a decade.

The Pluto mission is especially time dependent. If the mission doesn't launch by 2006, it will lose any chance of receiving a boost from Jupiter's gravity to propel the spacecraft to the outer solar system. Also, by the time a spacecraft launching later than 2006 reached Pluto, chances are that the planet's atmosphere will have frozen to the surface as Pluto moves farther from the Sun on its elliptical orbit. This generation—and the five to follow—could be denied the chance to study Pluto's tenuous atmosphere and uncover whatever clues the planet holds to the origin and evolution of our solar system.

The Planetary Society was instrumental in last year's fight to save the Pluto mission, which resulted in the US Congress adding funds for the mission over the administration's objections. NASA proceeded to select the *New Horizons* mission to Pluto proposed by the Johns Hopkins University Applied Physics Laboratory. *New Horizons* was scheduled to launch in 2006, reach Pluto in 2015 or 2016, and then continue to explore objects in the Kuiper belt, those bodies that circle the Sun beyond the orbit of Neptune. Cancellation of the mission will significantly delay any future attempt to reach Pluto—and cost more, too.

The proposed 2003 budget would also cancel the Europa orbiter mission, to be built by Caltech's Jet Propulsion Laboratory. Scientists strongly suspect Europa has an ocean of liquid water beneath its icy crust—an ocean that may contain clues to the possibility of extraterrestrial life. In previous years, this possibility led the administration and NASA to rank a Europa mission as high priority. Now any Europa mission is likely to be far more expensive and probably not launch for a decade or more—that is, if NASA must wait until nuclear propulsion is developed.

NASA officials have made it clear that nuclear propulsion will not be available, even under the most optimistic scenarios, for at least 10 or 15 years. And while a Pluto mission could fit within the guidelines of the proposed New Frontiers program, a Europa mission would not.

The proposed New Frontiers program is a welcome development. Missions in the program would be larger, more costly, and more capable than the Discovery missions now in development. A New Frontiers mission could be flown every two to four years. Costs would be capped at $650 million, and the competitive process in place for mission selection would encourage a wide range of interesting proposals.

The *New Horizons* mission to Pluto now under development—and canceled in the proposed budget—fits the New Frontiers guidelines exactly. New Frontiers would be off to a great start if Congress would appropriate the money to include *New Horizons* in the New Frontiers program, thus preventing the cancellation of this promising mission.

Louis D. Friedman is executive director of The Planetary Society.

Where Should We Go?

Last year, NASA asked the National Research Council (NRC) of the National Academy of Sciences to conduct a "decadal survey" of potential targets for planetary exploration. The NRC was charged to examine the priorities for planetary science and to recommend missions to be conducted over the next decade. It was hoped that this process, which has been effective in directing funding for large projects in the astronomy and astrophysics communities, will similarly benefit the planetary sciences.

The study results should carry weight among those deciding about the Pluto and Europa missions. Unfortunately, the results will not be officially released until June or July. However, we expect both the Pluto and Europa missions to rank highly, and we hope the survey will help convince Congress to restore these missions to the coming year's budget.

In cooperation with the NRC, The Planetary Society conducted a public poll about priorities for planetary exploration. Visit our website, *planetary.org*, to see the results. —*LDF*

Why the Shifting Support?

Why did the administration, through its Office of Management and Budget, shift so radically in its support for outer planets exploration? One year ago, it ranked the Europa orbiter mission as high priority. Now the mission is canceled, along with the Pluto mission. Might this be an effort by the administration to show Congress who's boss? Very likely the administration chafed over Congress' granting of funds last year to save the Pluto mission in response to public pressure but in defiance of the administration's wishes.

Such is power politics in Washington. Now, it will be up to The Planetary Society, our scientific colleagues, and the public to convince Congress to restore outer planet exploration to the American space program. Last year, Planetary Society members led the way in persuading Congress to restore the Pluto mission. Now, we must work together to again make our voices heard.

We urge you to follow the latest developments in the 2003 budget on our website, *planetary.org*. We must prepare to take action. —*LDF*

COSMOS 1 UPDATE: SCHEDULE SLIPS, CONFIDENCE GROWS

BY LOUIS D. FRIEDMAN

As The Planetary Society continues to progress toward the launch of *Cosmos 1*, the first solar sail, I have both good and bad news to report. First, the good news: flight hardware is being manufactured, delivered, and tested, and we are moving steadily toward a launch this year. Now, the bad: our schedule has slipped, and we will not launch before September.

It's an axiom of space mission development (and of any large, complex project) that management balances four variables: cost, performance, schedule, and risk. For our solar sail project, increasing cost would mean additional funds that neither we nor our sponsors have, while easing up on performance requirements would endanger our goal of orbital flight. And we simply cannot increase risk. Everything about *Cosmos 1* is unprecedented; so, while every space mission is inherently risky, ours, being a first, is doubly so. Schedule is the only variable that can give.

Many factors contributed to the schedule slip. They include the following:

- This winter, a huge blizzard crippled central Russia, causing the plant manufacturing our solar arrays to lose three weeks of production. Consequently, we lost our place in the testing queue, which rippled into a five-week delay.
- The Institute for Space Research and the Babakin Space Center, our prime contractor, decided to build a much more capable spacecraft than we had originally planned, with full redundancy to decrease risk and a higher data rate to maximize information return. This increased the craft's development time.
- During testing, our team experienced a higher-than-expected failure rate with commercial chips purchased in Europe. We had to order replacements.
- These delays adversely affected the existing solar sails, possibly degrading the sail material. So, Babakin manufactured new sails for the flight spacecraft.

While we regret the schedule slip, we are now more confident about our chances to fly a successful mission. Both our Russian contractors and the American experts on our review team share this opinion. We know that missions rushing to meet a fixed launch date are riskier than those able to accommodate developmental slips. We are comfortable with our progress.

We expect to set a launch date soon. Meanwhile, you can check our website, *planetary.org*, for updates on our progress. Again, we must thank Cosmos Studios for accepting the risk of sponsoring this project. We also acknowledge the valuable donations to the project from Peter Lewis and you, the members of The Planetary Society. —*Louis D. Friedman*

Harris M. (Bud) Schurmeier inspects the mechanical engineering model of the* Cosmos 1 *spacecraft. Schurmeier, the former associate director of the Jet Propulsion Laboratory, leads the system review of the solar sail project as a consultant to The Planetary Society.

Above: Here is a close-up view of the solar sail blade (left) packed into its protective bag. This blade is ready for flight. At the center of the frame, the motor for pitching the sail blades is visible. The white ties at right simply hold the protective bag over the sail before flight.

Right: The mechanical engineering model of the* Cosmos 1 *spacecraft sits atop the launch vehicle interface on a vibration test table. One blade of* Cosmos 1*'s solar power array is facing the camera. The khaki-colored bags are holding the solar sail's blades—there are four in each of two planes around the spacecraft. Several antennae that will be used in the telemetry and navigation systems are visible at the top of the vehicle.

Photos: Louis D. Friedman

Questions and Answers

Now and then, we publish an article in *The Planetary Report* that really stirs things up. "The Strange Acceleration of *Pioneer 10* and *11*" by John D. Anderson, Philip A. Laing, Eunice L. Lau, Michael Martin Nieto, and Slava G. Turyshev in the November/December 2001 issue was just such an article. Here, authors Michael Martin Nieto, John D. Anderson, and Slava G. Turyshev answer some questions representing those most frequently asked about the piece.
—Donna Stevens, Associate Editor

Direction and acceleration questions:

You left me confused about where the* Pioneer *spacecraft are going. The thrust of your article is that the spacecraft are accelerating toward the Sun, but the photo caption on page 16 states that* Pioneer 10 *is heading toward the red giant Aldebaran. How can it be headed two places at once?
—Richard H. Smith,
Burbank, California

In "The Strange Acceleration of* Pioneer 10 *and* 11,*" you state that a signal from the spacecraft can be interpreted as an anomalous acceleration directed toward the Sun. But if the spacecraft is moving away from the solar system, how can there be an acceleration toward the Sun?
—Ed Anderson,
Midland, Texas

This process works like a brake. If you are driving down the highway and brake a little, your acceleration is opposite to your direction of motion. Mathematically, an acceleration is a change of velocity with time. As your car starts from zero velocity and speeds up to 65 miles per hour (105 kilometers per hour), it is accelerating. Scientists call that a positive acceleration—in the same direction as the velocity. When you slow down from 65 to zero, you normally think of that as braking or decelerating. But to the scientist, it is still a change of velocity with time. So, it is an acceleration (a negative one this time, because it is in the direction opposite to the velocity). Although the extra negative acceleration (braking) toward the Sun is slowing *Pioneer 10* down, it is still heading toward Aldebaran.
—MICHAEL MARTIN NIETO,
Los Alamos National Laboratory

Because we have no evidence for how the anomalous acceleration behaves beyond 80 astronomical units (AU, the distance between Earth and the Sun), it is impossible to predict the eventual fate of the *Pioneer* spacecraft. We have analyzed data only to the middle of 1998, so although the Deep Space Network has successfully tracked *Pioneer 10* out to about 80 AU (see box), we have not yet analyzed any data beyond 70 AU. Both the Sun's Newtonian acceleration and the *Pioneer*s' anomalous acceleration are directed toward the Sun, but both must overcome the rapid outward speed of the *Pioneer*s that resulted from their close flybys of Jupiter and, for *Pioneer 11*, Saturn.

In 1987, at the beginning of the data interval we are studying, the speed of *Pioneer 10* was 13.14 kilometers per second (29,393 miles per hour), with a radial component away from the Sun of 12.849 kilometers per second (28,742 miles per hour). This is more than enough to eject *Pioneer 10* from the solar system in the absence of the anomalous acceleration (the required escape velocity at the 1987 distance of 40 AU was 6.659 kilometers per second, or 14,896 miles per hour). But if the anomalous acceleration lasts indefinitely at its current value, escape will never happen. Instead, the spacecraft will slowly decelerate until, at 2,600 AU, the anomalous acceleration will equal the Newtonian acceleration.

As the Newtonian acceleration weakens even more according to the inverse square law, the anomalous acceleration will dominate and eventually bring the spacecraft to a stop. Our determination of the acceleration is uncertain by 15 percent, and it turns out that the stopping distance is uncertain by about the same percentage. But it is most likely between 426,000 and 580,000 AU, and it would take between 355,000 and 485,000 years to get to this point.

If that happens, the eventual fate of the *Pioneer*s will be to join the Oort cloud of comets. There, they could be perturbed by encounters with one or more comets and eventually fall back to the Sun at practically any perihelion distance—or, if unperturbed, they could return to the same orbital radius from which they were ejected: 5 AU for *Pioneer 10* and 10 AU for *Pioneer 11*. The time needed for them to return is the same as the time they'd need to get to the Oort cloud. Hence, we are looking at a time approximately 800 thousand years in the future for the possible return of the *Pioneer*s.

By then, the Sun should look pretty much as it does today, but how Earth would look, and whether there would be a civilization in the solar system, is anybody's guess.
—JOHN D. ANDERSON,
Jet Propulsion Laboratory

Dust and gas questions:

I wonder if this anomaly couldn't be explained by a higher-than-expected

density of interplanetary dust and/or gas? How much dust or gas would be required to account for the anomaly?
—Peter Mansbach
Bethesda, Maryland

Since there are many theories about the contents of interstellar space that account for galactic motion, why couldn't interplanetary space harbor the same material?

Also, the article is not clear on whether the deceleration has been constant or is only occurring beyond Pluto. Only one number is given, so I presume the deceleration started at launch.
—Alwien M. H. Dierl
Long Beach, California

In fact, there are ways to measure the type of matter these letters mention. Dust collectors on spacecraft, as well as infrared absorption measurements from spacecraft looking at distant objects, yield values that do not fit the amount of material needed for this anomaly to be caused by a drag force.

Further, the amount of matter required either in Kuiper belt objects or in the form of dark matter conflicts with particle detection observations for the former and with gravitational observations for both scenarios. For example, about 0.0003 solar masses out to 50 AU would be needed in a spherical distribution, with a specific unusual density profile. But only 0.0001 solar masses within the orbit of Uranus would cause disagreement with the solar system ephemeris. In other words, the planets would not be where we expect them to be.

With regard to Dierl's letter: the acceleration has been approximately constant between about 22 and 32 AU for *Pioneer 11* and 40 and 71 AU for *Pioneer 10*. (There are data further in for *Pioneer 10* that roughly indicate the same result, but these data have not been rigorously analyzed.) —MMN

The article on strange acceleration states that* Pioneer 10 *is about 79 AU from Earth. I thought that light took about eight minutes to travel from the Sun to Earth. If 1 AU is the mean distance from the Sun to Earth, and the spacecraft is 79 AU away, how could the authors support the phrase "the round-trip light time to* Pioneer 10 *is now approximately 24 hours"?

A little more than 10 hours is the sum of 79 x 8 minutes. Where am I mistaken?
—Jeff Appelbaum,
Summerville, Georgia

You have calculated the one-way time. The round-trip time is twice that. On March 2, 2002, the 30th anniversary of launch, *Pioneer 10* (now almost exactly at 80 AU) was recontacted (see box), and the round-trip radio travel time was then 22 hours, 10 minutes.—MMN.

While the* Pioneer *and* Voyager *spacecraft are heading away from the solar system (except for that mysterious residual toward us), they are really only entering a slightly different orbit than the Sun around the galaxy. Will they eventually return to our vicinity?
—Roger Williams,
Boulder, Colorado

Effectively, the answer is no. The relative velocities of the *Pioneer* spacecraft to the solar system are about 12 kilometers per second (26,843 miles per hour). The velocity of the solar system in the galaxy is about 220 kilometers per second (492,124 miles per hour), and the orbital period around the galaxy is about 250 million years. So, the orbits of the spacecraft will intersect the Sun's orbital plane (not the orbit) only about every 125 million years. Further, since the Sun has a different velocity, it won't be there when the *Pioneer*s are.
—MMN and SLAVA G. TURYSHEV

In honor of its launch 30 years ago, a signal was sent to *Pioneer 10* on March 1, 2002 from the Jet Propulsion Lab's Deep Space Network (DSN) in Goldstone, California. Twenty-two hours and 10 minutes later, researchers monitoring a 70-meter dish antenna at the DSN facility in Madrid received the spacecraft's response.

The mission's principal investigator, James Van Allen of the University of Iowa, reports that the cosmic ray instrument on *Pioneer 10* provided 44 minutes of data. The data show that the spacecraft is still under the delayed influence of solar activity and has not yet reached the boundary of the heliosphere.

This screen capture shows what was on the computer monitor in the control room of NASA's Ames Research Center when* Pioneer 10*'s signal was received.
Image: ARC/NASA

At the time of contact, *Pioneer 10*'s distance from the Sun was nearly 80 AU; its speed relative to the Sun was 12.24 kilometers per second (27,380 miles per hour). The spacecraft's distance from Earth was 11.93 billion kilometers (7.41 billion miles). *—DS*

Society News

Two Exciting Expeditions!

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Voyage to Antarctica and the South Shetland Islands, December 24, 2002–January 5, 2003

Considered by scientists and travelers to be one of the most pristine regions and challenging environments on Earth, Antarctica offers magnificent wilderness areas featuring awesome mountain ranges, breathtaking tidewater glaciers, and dazzling scenery. A top scientist from The Planetary Society will join Willy Weeks in coleading the New Year expedition.

For reservations and detailed brochures, call Betchart Expeditions, (800) 252-4910 or (408) 252-4910.

Optical SETI Telescope Installed

Helped along by a grant from The Planetary Society, the new optical SETI telescope has been installed in its permanent home at the Oak Ridge Observatory in Harvard, Massachusetts. The telescope was delivered on February 14, 2002 by its builder, Ray Desmarais of Arkansas, and put carefully into position using the observatory's retractable roof. It was then set into its pier, where it will spend the rest of its working life. Boasting a 72-inch (182-centimeter) primary mirror, it is now officially the largest optical telescope in the US east of the Rockies.

According to project leader Paul Horowitz of Harvard University, the installation of the telescope marks a giant step toward the launch of the SETI experiment, when the telescope will begin searching for an alien signal. Nevertheless, much still remains to be done. The telescope must be wrapped in Mylar to protect its mirrors from the elements, and the complex electronics needed to conduct the search must be built and installed. Upon completion of the work later this year, the telescope will begin searching the skies for light bursts as short as one-billionth of a second.

You can follow the progress of the work on the optical SETI observatory by visiting the SETI section of our website, *planetary.org*.

—Amir Alexander, Web Editor

You Are Invited!

On June 8, 2002, The Planetary Society will pay tribute to Bruce C. Murray with a gala dinner entitled "Continuing the Voyage."

The dinner, which will be held at the Millennium Biltmore Hotel in Los Angeles, will honor Murray's visionary leadership of The Planetary Society and his lifetime commitment to space exploration. Ray Bradbury, Tom Young, and A. D. (Bud) Wheelon are chairing the event, whose honorary committee includes Buzz Aldrin, Ann Druyan, Nichelle Nichols, Bill Nye, Robert Picardo, Majel Roddenberry, and Neil deGrasse Tyson.

Along with an impressive list of guests, the evening will include an auction, entertainment, and gourmet dinner. In addition, a tribute journal is being prepared. You may purchase a page, or part of a page, of the journal if you would like to send Murray a message of congratulations.

Reservations for the event are required and limited. Call Vilia at (626) 793-5100, extension 231, for more information.

—Charles Nobles,
Chief Operating Officer

Society Event in the Republic of San Marino

On March 9, 2002, in the Republic of San Marino near Rimini, Italy, The Planetary Society presented a public panel entitled "Other Earths, Other Voices? The Search for Extraterrestrial Intelligence." Panelists included Dan Werthimer, chief scientist of SETI@home; Claudio Maccone, cochair of the SETI committee of the International Academy of Astronautics; Stelio Montebugnoli, director of the CNR SETI program in Medicina, Italy; Ivan Almar of the International Academy of Astronautics; and Amir Alexander of The Planetary Society. The panel drew a crowd of close to a hundred people, including many Planetary Society members. The event was held as part of EUROSETI, The First European Conference About the Search for Extraterrestrial Intelligence, which took place in San Marino on March 8–9. *—AA*

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Mark A. Garlick received his Ph.D. in astrophysics in 1993 and went to work as a researcher at Britain's University of Sussex in Brighton. In 1996, he began writing and illustrating articles on astronomy for magazines and newspapers. He now works full-time as a science writer and artist. Garlick's work has appeared in *Scientific American, New Scientist, Astronomy, Sky and Telescope,* and *Asimov's Science Fiction*.

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