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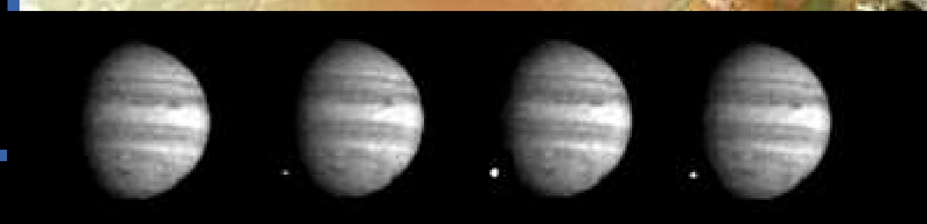


Glorious *Galileo*

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Table of Contents

Volume XXIII

Number 5

September/October 2003

Features

6 "There was nothing like *Galileo*. . ." John Casani Remembers

The mission that became *Galileo* was proposed in 1976 as a relatively simple fields-and-particles orbiter that would carry an atmospheric probe to Jupiter. It was too simple to last. *Galileo* grew into one of the most complex and ambitious exploratory missions ever launched—and one of the most jinxed. Again and again, the mission changed launchers, was redesigned—even split in two—and restored, then bumped off its launcher, nearly canceled, and forced onto a tortuous trajectory that sent it on a loop-the-loop path to Jupiter. And that's before the equipment problems started. John Casani led the mission team through *Galileo*'s incredible saga and shares his memories here.

11 Casani Aborts Retirement, Heads for Jovian Realm—Again

Some people just cannot resist a challenge. John Casani has reentered the fray of planetary missions, leading the development of a mission that could initiate a new era of exploration. The Jupiter Icy Moons Orbiter is being designed as the first mission that would use nuclear propulsion to explore the planets.

12 *Galileo*'s Greatest Hits: The Scientists' Choices

The scientists of the *Galileo* mission were an extraordinarily persistent bunch. Many of them were on the mission for nearly a decade before the spacecraft launched and waited 6 years for it to reach its destination. Their persistence paid off with an extraordinary array of discoveries. Each scientist probably has his or her favorite, so we felt the best way to cover "*Galileo*'s Greatest Hits" was to ask the people who made them happen.

Departments

3 Members' Dialogue

4 We Make It Happen!

19 World Watch

20 Society News

From The Editor

The (seemingly) never-ending story is over: the *Galileo* spacecraft, which has been exploring the Jovian system since 1995, is sacrificing itself to protect whatever life-forms might exist on the icy moon Europa. There's not enough propellant left for spacecraft controllers to guide *Galileo* safely through another orbit of Jupiter, so to ensure it never can collide with Europa, it was targeted to enter Jupiter's massive atmosphere, where it will be safely obliterated.

If Hollywood had produced a movie with as many plot twists and turns, hopeless situations, and victories snatched from the jaws of defeat as the *Galileo* mission has seen, critics would have roasted it for being unbelievable. But, as is often the case, the real story is stranger than any we can imagine.

In this special issue of *The Planetary Report*, we have tried to let the mission managers and scientists tell the story in their own, different ways. As you read through these pages, keep in mind the extraordinary dedication, skill, knowledge, and sheer stubbornness it took to launch this spacecraft, keep it flying, and see its data returned.

Galileo was a triumph of the will to explore—and of the human spirit. That is what we seek to continue with the support of The Planetary Society's members.

—Charlene M. Anderson

On the Cover:

Clockwise from upper left, these images from *Galileo* are Jupiter's atmosphere (false color); Culann Patera on Io (false color); comet Shoemaker-Levy 9 hitting Jupiter; Europa (false color); Asteroid Ida and its moon, Dactyl; and Ganymede. Images: JPL/NASA

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Members' **Dialogue**

A Good Read

Thank you for the article about the announcement of the landing sites chosen for the Mars Exploration Rovers [see "A Place to Call Home: Selecting the Next Mars Landing Sites" in the May/June 2003 issue of *The Planetary Report*].

Congratulations for writing the story in such an interesting fashion and for including so many important details and clear photographs. It is the best writing I have read yet on the subject—the most readable and the most human.

I will be sending your website address to my three grown sons in the hope that they will enjoy it and become part of the growing excitement over the approach of the next adventure in this real-life Mars saga.

—Mrs. J. B. ROWBOTHAM,
The Pas, Manitoba, Canada

After *Columbia*

In spite of the *Columbia* tragedy, two people continue to orbit Earth on board the International Space Station. There is both hope and sad irony in this observation. One of the most troubling aspects of the *Columbia* disaster was being reminded that there was no direct way to detect damage on the orbiter prior to reentry, and that, even if such damage could have been detected, there was no way to repair it.

Imagine, however, a space station not just "operational" but fully capable, with a habitation module able to support a full-time crew of six and an automated crew return vehicle designed to carry them back to Earth in an emergency.

If the United States is going to continue to have a manned space flight program, and I vigorously argue that it should, we owe it to our astronauts to see to it that the program is robust and adequately funded. The aging shuttle fleet has served us well in its initially planned operations and all of its other capacities, but it is time to limit its duties to those it was initially designed for while we improve the International Space Station and begin to build the next generation of space planes.

As the problems that doomed *Columbia* are fixed, in the wake of the accident review board's report, we have an opportunity to improve upon a space program that is already a tremendous source of national pride. The cost will not be that great, and we owe it not only to the *Columbia* Seven but also to ourselves.

—TOM SARKO,
Palm Beach, Florida

From Down Under

I am pleased that the metric system takes primacy in *The Planetary Report*, but I notice that the editor refers to "Earth's early winter" in "From the Editor" in the May/June 2003 issue. This should, of course, refer to the northern hemisphere, as we in the antipode experience "early summer" at that time.

Otherwise, keep up the good work.

—TIM SPENCER,
Brisbane, Queensland, Australia

From *planetary.org*

Here is a sampling of the comments our website readers have sent in.

Wow! Early 2004 is going to be great. *Spirit* and *Opportunity* should be sending back fantastic images and data by then. It was a pleasure to read "Mars Exploration Rover *Spirit* Soars to the Red Planet" [June 10, 2003].

I am a proud member of The Planetary Society and I look forward to the Mars Exploration Rover updates from the Society's representatives.

—STEPHEN HITCHMAN,
Kitchener, Ontario, Canada

Thanks, Emily, for an insider's look at the launch [see "Watching *Spirit* Launch to Mars," June 10, 2003]. It's so refreshing to see people doing something well, simply because they love it. Good job!

—DAVE PACKARD,
Baldwinsville, New York

This is a great idea [see "Biff Starling Launches for Mars," June 10, 2003]. I'm excited about it and I'm 33 years old. It's just the kind of thing that might get kids interested in the Mars Rovers. And I have to admit, I'll be reading the web log too.

—BONNIE RUSSELL,
Dearborn, Michigan

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We Make It Happen!

by Bruce Betts

The full-size (15-meter) Cosmos 1 *solar sail blade is shown deployed (right) in the lobby of New York's Rockefeller Center. The upper part, or end, of the solar sail blade is shown in the inset.*

Photos: Philip Greenberg. © 2003 by The Planetary Society and Cosmos Studios

Cosmos 1, The Planetary Society's attempt to fly the world's first solar sail, is our largest and most ambitious project ever. With this project, we seek to demonstrate a new kind of space propulsion. This is pretty darned ambitious for a space interest group (the first ever space mission conducted by such a group) and our partners. It is made possible by you, our members, and through our partnership with Cosmos Studios, a science-based entertainment company led by Ann Druyan. We have some news to update you on, both technically and regarding public inspiration.

Solar Sailing: What's Up with That?

Solar sailing utilizes the pressure of sunlight pushing on a giant reflective area to move a spacecraft. On Earth, with atmospheric effects far outweighing light pressure effects, we don't notice that light carries momentum (i.e., exerts a force or push). In the vacuum of space, however, those little pushes from light can be a significant effect, particularly when you use large sails made of thin, highly reflective material (*Cosmos 1* uses Mylar-like material that has been aluminized). Sunlight pressure is powerful enough to push spacecraft between the planets. Beyond the solar system, space sailing can be accomplished using powerful lasers focused over long distances. Solar sails might help us realize the long-sought dream of interstellar flight, but no one has taken the first step of demonstrating it, the equivalent of that first Wright Brothers flight 100 years ago. This is what we are trying to do, and we'll be trying it in Earth orbit. So, where are we?

Dropping Spacecraft: Don't Worry, It's a Good Thing

In mid-August, we passed a critical milestone: the Volna launch vehicle we will use—a converted Russian submarine-launched ballistic missile—demonstrated that it is now ready for orbital missions. The Volna's readiness has been the most worrying factor in our mission. In two suborbital flights, the third stage failed to properly release its payload. The first failure was during our suborbital test in July 2001; the second came several months later in the test of a European Space Agency craft.

The separation problem now seems to have been fixed. At the Makeev Rocket and Test Center in Miass, Russia, engineers tested the entire launch sequence, including the tricky separation of the solar sail payload from the rocket. To simulate conditions in space, they used a vacuum chamber equipped with a 60-meter (200-foot) tower. A complete engineering model of the solar sail spacecraft was bolted on to the third stage of the Volna and dropped from the tower. As it fell, explosive bolts were triggered to separate the payload from the stage. Everything went exactly as planned. The model appears to have come through absolutely intact. After the project team inspects the engineering model upon its return to Babakin Space Center, we will receive an official report on the test.

Centennial of Flight Display

For three weeks in July and August, we deployed one of our engineering models of a solar sail blade at the Centennial of Flight Exhibition at Rockefeller Center in New York City. This 15-meter-long triangular blade will have seven identical friends in the actual solar sail spacecraft, but even on its own, it was a very impressive sight. *Cosmos 1* was selected to be part of this celebration of the hundredth anniversary of powered flight. The exhibition displayed icons of the past 100 years of flight, including life-size models of the Wright Flyer, a Mercury Redstone rocket, and an *Apollo* command module. Tens of thousands of people saw the sail blade every day in the first major public display of this future space propulsion technology.

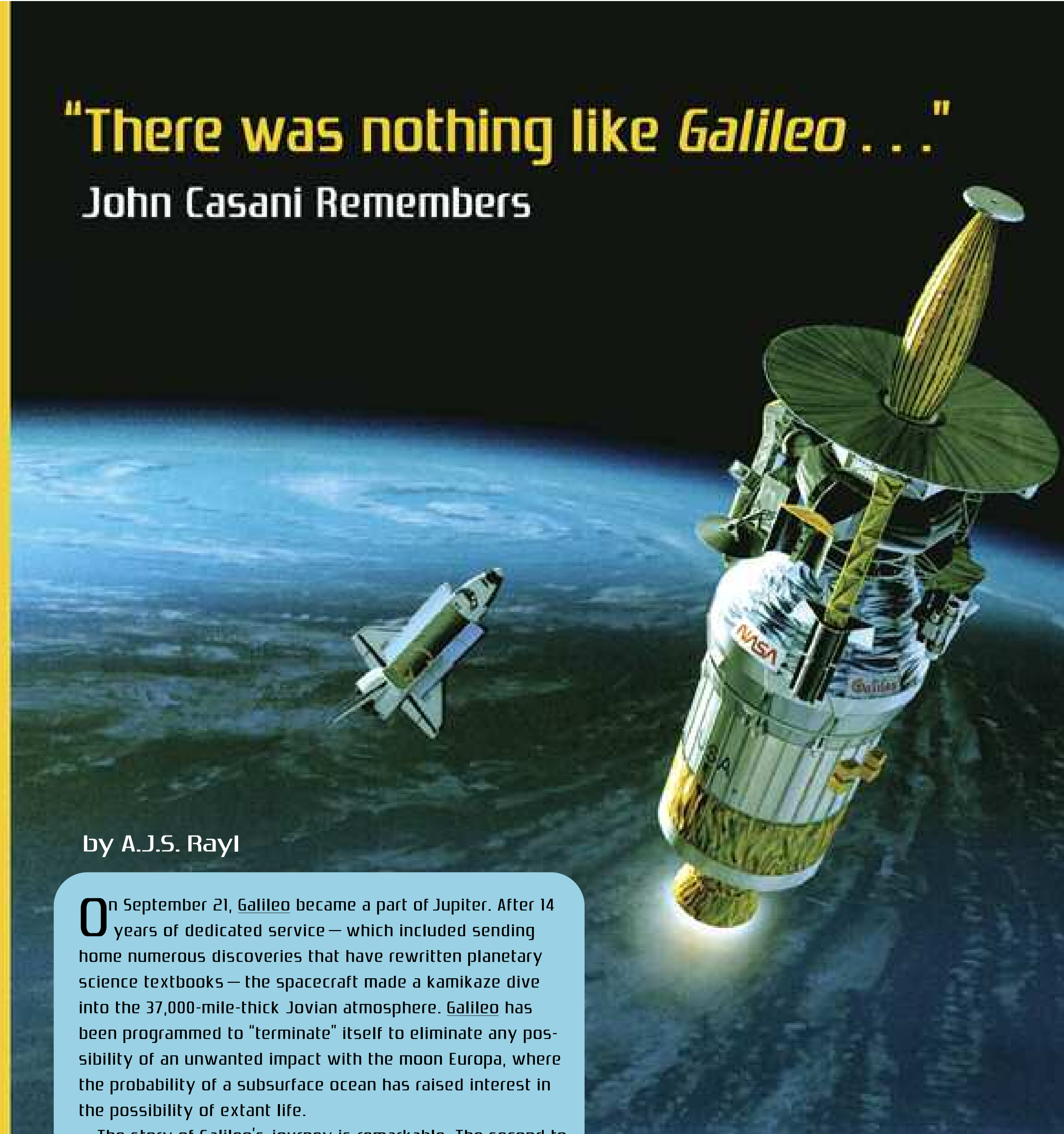
Flight Spacecraft and Launch

The flight version of the spacecraft is being assembled at the Babakin Space Center near Moscow. Our team of engineers and scientists is still testing the flight software and hardware. For the most part, these tests are going well, but in space everything *must* go well. The test program is proceeding slowly and methodically. We are not rushing or taking any risky shortcuts and therefore will most likely not launch until the first half of 2004. To keep updated on our progress and schedule, check our solar sail website: *planetary.org/solarsail*.

Bruce Betts is director of projects for The Planetary Society.

"There was nothing like *Galileo* . . ."

John Casani Remembers



by A.J.S. Rayl

On September 21, *Galileo* became a part of Jupiter. After 14 years of dedicated service—which included sending home numerous discoveries that have rewritten planetary science textbooks—the spacecraft made a kamikaze dive into the 37,000-mile-thick Jovian atmosphere. *Galileo* has been programmed to "terminate" itself to eliminate any possibility of an unwanted impact with the moon Europa, where the probability of a subsurface ocean has raised interest in the possibility of extant life.

The story of *Galileo*'s journey is remarkable. The second to last of the "big" planetary missions (*Cassini* arrives at Saturn in 2004), it is no small miracle that *Galileo* flew at all. But fly it did, returning invaluable science despite a crippling technical failure and surviving four times as long as expected. In honor of this exploratory pioneer, the mission's original project manager, John Casani, who guided it through budgetary crises, political storms, disasters big and small, and various redesigns, took some time recently to reminisce about the trials and tribulations the team endured to get the spacecraft on its way.

It was clear, but colder than usual for Florida, on that January morning in 1986. *Galileo* Project Manager John Casani and others taking part in the review of the Centaur rocket, which was finally to launch the Jovian mission in a few months, decided to take a break and watch the shuttle take off. They regrouped in a corner office that had floor-to-ceiling windows and a clear view of the launchpad. In just four months, *Galileo* would be out there, ready to make history as the first planetary mission

Galileo *left Earth on October 18, 1989, beginning its amazing 14-year journey of discovery. The spacecraft, sitting atop its inertial (originally named "interim") upper stage, had just been released from the space shuttle in this artist's rendition.*

Painting: Ken Hodges for NASA

launched from a space shuttle. After nine years of politics, technical problems, ingenious fixes, and the traditional blood, sweat, and tears, that day couldn't arrive quickly enough for Casani and other team members.

On this particular day, *Challenger* was out there, shimmering in the bright winter morning. The launch was moving like clockwork: ignition . . . liftoff. . . rollover. Commander Dick Scobee acknowledged maximum acceleration, and those watching from the ground saw the shuttle soaring majestically into the blue sky. Suddenly—it was gone. Plumes of white, orange, and yellow smoke trailed from the explosion. Silence fell on the room, as it fell on living rooms all across the country. "We were in shock," Casani remembers, "just like everyone else."

Later that day, Casani assembled the members of the *Galileo* team who were on location at Cape Canaveral. Amid the emotions of the immediate loss of the *Challenger* and its crew of seven, he confirmed what they already knew and did his best to rally his troops. "We know there's not going to be a launch this May," he began, "but we're not done yet."

The next day, Casani boarded a plane and returned to the Jet Propulsion Laboratory (JPL) in Pasadena, California. He called the rest of the *Galileo* team together, climbing up on a cafeteria table to deliver essentially the same message. "We have made an investment and commitment to this mission, and so has Congress, and the science community. . . . Even this tragic, horrible event cannot diminish the value of finishing what we started. We just need to find a solution."

"There was real uncertainty," Casani recalls now, some 17 years later. "I knew it was going to cost more money, that we'd have to put a plan together and go back to Congress." He also knew he had to share the uncertainty. What he didn't know was that more setbacks were yet to come.

The space science community first began to entertain the idea of a mission to Jupiter in the mid-1960s, as *Mariner 4* was heading toward Mars. More than a decade later, during the summer of 1977, NASA approved the Jupiter Orbiter with Probe (JOP) mission. Even before the project officially began, however, it encountered turbulence. As NASA gave the green light, Congress flashed the red light, motioning to kill the mission with the budgetary axe.

The JOP mission escaped the financial guillotine, in part because it was being developed in parallel with the space shuttle to provide a cargo for the shuttle. It would be launched from the shuttle's cargo bay with a three-stage, interim upper stage (IUS) rocket to be developed by the United States Air Force. The mission was approved for launch in 1982, a particularly opportune time, for it would put the spacecraft at Jupiter only two and a half years later, in 1985. Beyond the scientific integrity of a mission to the solar system's biggest planet, NASA officials were well aware that this mission would boost the image of the Space Transportation System (STS) by helping it live up to the promise that sold it as "the key" to America's future in space. The early turbulence, though, might have been viewed as an omen of troubles to come.

Just a few weeks after the Jupiter mission was budgeted, in early September 1977, John Casani entered the picture. He had been managing the *Voyager* mission, and a day or two after the second spacecraft launched [from Cape Canaveral], he was riding in a car with Bob Parks, then the assistant lab director for flight projects at JPL, to the airport to return to Pasadena. "He said he had a new job for me," recalls Casani.

For Casani, the decision was easy. Jupiter is the largest planet in the solar system and one of the most mysterious. Despite having 2.5 times more mass than all the other planets in the solar system combined, it rotates faster than any other planet. Giant wind systems band Jupiter in warm shades of rust, yellow, and brown. Appearing as a bright star in the night sky, the big planet has always been alluring for its size and beauty. More important, scientists believed that clues about how the solar system formed 4.5 billion years ago were to be found in the Jovian realm. Getting there and investigating Jupiter in a way no other spacecraft ever

Galileo *ended its own long, productive life on September 21, 2003 when it plunged into Jupiter's atmosphere, where the giant planet's tidal forces tore the spacecraft apart. This move was designed to eliminate the chance that Europa—and any possible life there—could be contaminated should* Galileo *crash into that icy moon.* Painting: Michael Carroll

had—*Voyager* had not yet returned any data—would be significant. "The challenge was just so intriguing," he says simply.

It was a challenge, however, that came with plenty of obstacles, the first of which—a rather critical engineering problem—was waiting for Casani and crew as they moved into the project at JPL. Casani explains: "This mission was proposed in 1976 largely by a group of fields-and-particles scientists—Jim Van Allen [of Van Allen Radiation Belt fame] headed the team at NASA Ames Research Center in Mountain View, California. It was proposed without the input of the remote sensing people, who were all focused at that point on the *Viking* mission, which had two spacecraft in orbit at Mars and a couple of landers on the ground, all with cameras."

The point is not insignificant, he says, because these two communities—fields and particles, and remote sensing—also characterize the two basic types of instruments designed for spacecraft. Casani continues: "The fields-and-particles scientists behind this mission were interested in instruments that measure what's going on right around the spacecraft—magnetometers, for example, or devices that measure cosmic rays or dust. Therefore, this group likes to be on a spacecraft that spins so their instruments can sample everything in the sky around the spacecraft. A spinning spacecraft is also an ideal spacecraft to launch a probe into Jupiter's atmosphere, because when it lets go of the probe, the spinning gives [the probe] a desired gyroscopic ability."

In contrast, remote sensing scientists collect their data with instruments that look for energy or information coming from the target, utilizing such devices as cameras and radars. Many in the scientific community and at NASA headquarters wanted a camera on board *Galileo* for the obvious reason that images would add to the mission and garner support from the general populace. "But cameras require some stability. In other words, remote scientists want a spacecraft that doesn't spin," Casani explains.

"There were big fights for a long period of time," he continues, recalling the meetings. "Finally, Van Allen said, 'Why don't we make most of the spacecraft spin, but also have a despun section and put the cameras on that?' Everyone finally agreed." Creating a spun-despun spacecraft was easier said than done. Although a few telecommunications satellites had supplied proof of principle, nothing had ever been designed to the scale or precision that a spacecraft going to Jupiter would need.

As 1977 gave way to 1978, JOP was renamed *Galileo*, in honor of Galileo Galilei, the Italian scientist who discovered four Jovian satellites—Ganymede, Callisto, Io, and Europa—and who dared confront the Catholic Church over the Copernican notion that the Earth revolves around the Sun. Not long after that, Team *Galileo* met its goal, producing a state-of-the-art, dual-purpose spacecraft. "It was about ten times harder to make work than anybody ever imagined," Casani says, reflecting. "That was, by far, the greatest engineering challenge."

The design was elegant. Constructed in three segments, *Galileo* featured an atmospheric probe that would carry seven instruments to take measurements during its dive into Jupiter's atmosphere, a nonspinning section of the orbiter carrying cameras and other remote sensors, and a spinning main section of the orbiter spacecraft that would include the fields-and-particles instruments. Together, these segments would investigate three broad aspects of the Jovian system: the planet's atmosphere, magnetosphere, and satellites.

The propulsion system was to be designed by the Germans, renowned since World War II for their engineering savvy, and NASA's contract with Germany to build the system made *Galileo* the first major international planetary exploration mission. Casani and other NASA engineers crammed a language course into the weeks before they headed to Germany for the first time in the winter of 1977.

A LONG AND WINDING PATH TO FLIGHT

During the next several years, production of the space shuttle—*Galileo*'s first step on the voyage to Jupiter—repeatedly fell behind schedule, sending the Jupiter mission on a rollercoaster of steep ups and potentially terminal downs.

In March 1979, for example, *Voyager* returned breathtaking images that revealed in detail for the first time some of the wondrous characteristics of giant Jupiter and some of its extraordinary moons. These long-awaited data served to inspire and further drive the *Galileo* team. The public was, generally speaking, awed. Not long after *Voyager*'s mesmerizing pictures of Jupiter hit front pages, however, Edward Boland, an extremely popular Democratic congressman from Massachusetts and then-chairman of the House Appropriations Committee, went on the attack. Charging that the Air Force's IUS rocket program was ill-managed, he attempted to force NASA to drop the IUS rocket plan and incorporate a higher-energy Centaur stage into its program. NASA rejected that advice and won the battle. Ultimately, however, it would lose the war.

Within a few weeks of NASA's rescuing *Galileo* again, Casani learned that the space shuttle would not be ready to launch during the critical January 1982 window. Moreover, the shuttle's performance would not be as originally promised, and it would ultimately have a lower payload capacity and fly less frequently. NASA officially scratched *Galileo* from the shuttle's manifest. All indicators were pointing to the mission's once again being canceled. One thing was certain: The best launch opportunity was lost. The solution was as simple as it was obvious to those involved with the mission: launch *Galileo* on the Titan-Centaur rocket system that launched *Voyager*. The only problem was politics. Because the shuttle was sold as a way to eliminate launches of expendable vehicles, such as the Titan, the very notion of turning back to Congress for $125 million for a Titan-Centaur launcher would only make NASA look foolish.

For many on the team, which at one point numbered around 300 people, the idea of dismembering the dual-spun spacecraft was almost unbearable. "But we had to do something, and we had no choice but to completely redesign the spacecraft and the mission," says Casani. "The idea of not getting to finish *Galileo* or actually having it permanently canceled was just not part of the equation. We were going to find a way to make it work."

They did. *Galileo* would be split in two, with the orbiter and atmospheric probe launched separately. It was a more expensive proposition, but NASA officials soon approved it, and *Galileo*'s launch was scheduled for 1984, with arrival at Jupiter in 1986.

Not long after the 1980 presidential election, however, word leaked to the public that the space shuttle was behind schedule and its performance challenged, and the IUS rocket system was over budget. In a matter of days, the special planetary version of the interim upper stage (IUS) rocket that NASA had been counting on was history, and once again, it looked like *Galileo* might be too.

On January 15, 1981, NASA administrator Robert Frosch announced the Centaur-in-Shuttle program. The good news was that the liquid-fueled Centaur was powerful enough to launch directly to Jupiter from the shuttle, and the team could go back to the original design—a combined orbiter/probe, spun-despun spacecraft to be launched in a single flight. The bad news was that it meant another two years' delay, with liftoff pushed to 1985. The team could have worked with this, but *Galileo*'s troubles were far from over.

In November 1981, David Stockman, director of the Office of Management and Budget in the Reagan White House, canceled the Galileo-Centaur program. The space science community rallied forces and Congress restored *Galileo*—but not the Centaur. That meant the two-stage IUS rockets cruised back into the Jupiter mission picture. By July 1982, however, the House of Representatives overturned Stockman's cancellation of Centaur, and Casani and crew returned once again to their mission design that would launch *Galileo* in one piece, with the Centaur from the shuttle, sending it directly to Jupiter.

By the end of 1982, five years after the Jupiter mission was first approved, *Galileo* was alive and well but still no closer to Jupiter. The fact that the team was still together is worth noting. "When people go through hard times together, there tends to be a bit of a bonding, and each of these people had made the commitment," offers Casani. There was more to it than that.

Although Casani directly managed only a handful of the hundreds of people who worked on the mission, he was well aware that the buck stopped with him, and he chose to set a policy of keeping each individual in the loop. "It was important that everybody understood what the situation was at any point throughout the entire mission—what the problems were, and where we stood," he explains. To keep everyone informed, Casani scheduled regular "all-hands" meetings at least twice a year, filling JPL's von Karmen Auditorium to standing room only. "The point was to have a dialogue, to keep people engaged." He also included the team's families with annual social gatherings. "But the single most important thing," he says, "was to share the uncertainty. That was what was really important."

In 1984, setbacks in the Centaur development schedule delayed *Galileo*'s launch yet again, this time by about a year, to May 1986, with arrival at Jupiter in 1988. Even so, *Galileo* was now complete and in the holding bay, waiting only for final tweaking of the Centaur. It seemed like nothing could stop it now. Then—*Challenger*.

In the days that followed the *Challenger* tragedy, the news for *Galileo* went from bad to "the worst," remembers Casani. "The shuttle guys had always been a little bit nervous about carrying 45,000 pounds of liquid oxygen and liquid hydrogen (fuel for the Centaur) in the belly of the shuttle," Casani recalls. "The folks at Johnson Space Center's Mission Control pretty quickly told us they were not going to entertain the Centaur."

The space shuttle program had been suspended indefinitely in the wake of the *Challenger* explosion; now the Centaur program was canceled almost on the spot. "That was probably the worst day in the whole mission," Casani sighs. "It meant we were going right back to the drawing board, again."

Galileo's upper stage once more became the less powerful IUS rockets. That meant the Jupiter mission couldn't be launched with the amount of fuel required to fly directly to Jupiter. "We were looking at everything . . . we even considered the Russians' heavy launcher, the Proton, but for a couple of reasons, it wasn't going to work," says Casani. "Finally, one of our engineers, Roger Diehl, came to my office and said 'Would you like to hear a kind of crazy idea?' "

Diehl and two other engineers—Louis D'Amario and Dennis Byrnes—had devised a unique flight path on which the spacecraft would orbit once by Venus and twice by Earth, to build up enough energy to "slingshot" itself to Jupiter. They nicknamed it Delta VEEGA, for Venus-Earth-Earth Gravity Assist. It would mean an increase in flight time to Jupiter from two and a half years to six years, but if it took advantage of these three gravity assists and risked a thermally undesirable close approach to the Sun, it could work. "I realized as soon as he started talking about it, this was our solution," Casani says. "I knew right then we would do it."

With the shuttle program restored in 1987, *Galileo* was granted a launch date of October 18, 1989 and was put on space shuttle *Atlantis*'s manifest. Arrival at Jupiter and the probe insertion were slated for December 1995, some 18 years after the mission saw its first green light. Those three years went by quickly, and the launch date held. Casani managed the project for more than 10 years, until January 1988. He moved on to become the assistant laboratory director for flight projects in 1987, a position he held until 1994, when then-JPL Director Ed Stone created a position for him, chief engineer. *Galileo* was the kind of mission, however, that Casani could never leave, at least in spirit.

GODSPEED, *GALILEO*

On October 18, 1989, Casani traveled to Cape Canaveral for the launch and watched *Atlantis* lift off with precision. Once in orbit, astronaut Shannon Lucid released the spacecraft from the shuttle's payload bay. At long last, *Galileo* was on the flight path to Jupiter, more than 12 years after the project began.

Galileo finally reached Jupiter on schedule in early December 1995. Although its prime mission ended two years later, the spacecraft was in good health, so NASA approved an additional two-year study, then another. In March 2001, the space agency extended the mission a third time, allowing the unmanned spacecraft to continue orbiting until September 2003. Throughout its service, *Galileo* consistently returned data.

The mission, which has spanned five presidential administrations, would ultimately boast seven project managers. Following Casani were Richard Spehalski, Bill O'Neill, Bob Mitchell, Jim Erickson, Eilene Theilig, and Claudia Alexander. Last year, with the onboard supply of propellant nearly gone, the flight team set *Galileo* on course for self-termination.

As *Galileo* plunged into the thick Jovian atmosphere, it was crushed by the intense pressure and pulled apart bit by bit, until eventually it broke down to its elemental atoms to dissipate among the atoms and molecules of Jupiter.

"I am proud of *Galileo*," Casani says in conclusion. "The accomplishment, the experience is not so much a sense of personal stuff—it was not personal. *Galileo* was very much a distributed effort among a lot of people, and all of us who were involved had something vital to do with that. I happened to have a prominent role, but it was not more important than any other. Every job had to be done right. . . . We committed ourselves to doing whatever it took and we were able to make it happen." He pauses for a moment in thought, then adds: "There was just nothing like *Galileo*."

A.J.S. Rayl is a web editor for the Society's website, planetary.org.

Casani Aborts Retirement, Heads for Jovian Realm — Again

In his words (as told to A.J.S. Rayl)

John Casani retired in August 1999. He returned almost immediately to work part time on various projects, including the short-lived Mars Sample Return mission, then went on to chair the review boards investigating the back-to-back failures of Mars Climate Orbiter and Mars Polar Lander. After that, in the summer of 2000, Charles Elachi, the new JPL director, asked him to come back full time. In November 2002, he began work on the Jupiter Icy Moons Orbiter (JIMO) project being developed in conjunction with Project Prometheus. Congress approved the budget for JIMO earlier this year, at which point, Elachi asked Casani to manage the project. Here, Casani describes JIMO. —AJSR

"Project Prometheus is the next step in exploration; it is the program to develop nuclear power and propulsion technology that will revolutionize our ability to explore the solar system. There are two underlying objectives for this project, and there is no priority. Both are equally important. Both are essential.

"The first objective is to make an investment in a technology, a capability that will allow the country, through NASA, to launch missions of solar system exploration that were never before possible, missions that just a few years ago weren't even imagined with any realism. We're talking about a nuclear fission, electric propulsion–powered spacecraft, a technology that will enable us to take solar system exploration to the next level.

"The second objective is to demonstrate that technology on a very, very high profile, highly important science mission, which, it has been decided, is the JIMO mission. The National Research Council's Decadal Survey, issued last spring by the National Academy of Sciences, declared a mission to Europa as the 'number one large mission' that NASA should undertake in the next decade. JIMO will orbitally characterize not only Europa but Ganymede and Callisto too.

"In the NASA life cycle terminology, there are two major pieces to any project up to launch: formulation, which is broken down into Phases A and B, and development, Phases C and D. Post-launch is Phase E. Right now, JIMO is at the very beginning of Phase A.

"Currently, three teams are working under contract: Lockheed Martin oversees one, Northrop Grumman Space Technologies (NGST) and Boeing the others. Each of those companies has three or four other companies with which it is working, and these teams will present preliminary designs down the road. Then we'll issue a Request for Proposals for the final product. Each of those three teams will then submit proposals. Then we'll select one. That process will take about two years from now. There's a lot of work to be done in the meantime.

"JIMO is targeted now in the 2011 to 2012 time frame. When we first started, the administrator [Sean O'Keefe] wanted it to be launched before the end of the decade. That would have required an enormous infusion of money right at the beginning, which in the practical sense is very impractical. Ideas like this take time to mature among the members of the science community. And, as *Galileo* and other missions have taught us, there are going to be people who are going to have second thoughts and wonder whether this is the right thing to do, especially because of the nuclear element. I do expect we'll have people who protest the use of nuclear power in space. Everyone is entitled to express his or her opinion. I do sincerely believe that.

"This issue, however, involves more than opinions. There are philosophies and principles that some people have, and I don't share the concern they're expressing. While I do believe that it's okay for them to voice those concerns, I also believe that what we are doing with Project Prometheus is right, and I know that we are doing it responsibly. There are risks, sure. But I believe they are acceptable risks. Some people will disagree with that. Some will assert moral authority in this arena I don't think is deserved.

"In any event, this is a process and it takes time to do the work and to develop what's required to do this mission. You can't push that too much. You just can't push a lot of money into the program while this process is going on, because these things have to sort of occur in the right sequence. It takes nine months to make a child, but can you speed it up with two or three women? From this point of view, then, we could fly as early as 2010, although the funding profile will be what limits JIMO and pushes the launch out.

"Although we couldn't justify developing the technology without this mission and we couldn't justify spending the money on the technology for this mission only, together, nuclear fission, electric propulsion, and the Jupiter Icy Moons Orbiter mission are the investment necessary if we are to further explore the solar system and beyond." ❍

Galileo's Greatest Hits— The Scientists' Choices

As September 21 approached—the appointed date
Jupiter—we asked ourselves how, in the limited
the amazing discoveries of this 14-year mission
was still traveling to its destination, with a swing by Venu
and Ida (and its moon, Dactyl), and a bird's-eye view of
was on to the planet itself, reaching it in December 1995
swirling atmosphere and settled into orbit about the plan
make 35 circuits and repeatedly fly by the four largest sa

The spacecraft might have kept flying, but it was runn
sion controllers used to steer the craft. Without steering,
moons —perhaps Europa, with its underground ocean t
into the giant planet's atmosphere, where it was crushed

How could we summarize the discoveries from such a
tists do it for us. We asked some of The Planetary Socie
choices of the most significant discoveries in their respe
"greatest hits" from one of the most successful and prod
mission to Jupiter. **—Charlene M. Anderson**

Torrence Johnson of the Jet Propulsion Laboratory has served as project scientist for the Galileo *mission from its beginning, and he had primary responsibility for making all the spacecraft experiments work together. His own research interests focus on the moons of the outer solar system, which he has been privileged to see through the robotic eyes of both* Galileo *and* Voyager.

Galileo's Greatest Hits

by Torrence Johnson

The *Galileo* mission has been spectacularly successful—a tribute to the spacecraft's developers and the teams that have flown it and analyzed its data over the years, overcoming a multitude of technical obstacles along the way. Scientifically, *Galileo*'s discoveries have involved nearly every discipline of space science, from probing the atmosphere of a giant planet for the first time, to surveying Jupiter's vast and energetic magnetic domain, to exploring "up close and personal" the big moons first seen nearly four centuries ago by the great physicist whose name our observing platform bears.

The mission's amazing revelations about the Galilean satellites have had perhaps the most meaning for me. Getting a first real look at Io, Europa, Ganymede, and Callisto a few years later as the *Voyager* spacecraft dashed by Jupiter was literally an eye-opener: volcanic Io; smooth, uncratered Europa! As we prepared for *Galileo*, we knew we were going to get even better information, but *Voyager* was a hard act to follow.

Almost as if the spacecraft sensed this challenge, the very first encounter with a satellite after it was in orbit produced one of the major results of the mission—the discovery of Ganymede's magnetic field. Understanding how this field is generated and maintained is a challenge to the theoreticians who study the internal structure and history of the satellites. This initial result was followed by seven years of surprises and revelations of layer after layer of complexities only hinted at in *Voyager*'s satellite results.

Callisto, the "dull sister" of the group as viewed by *Voyager*, turned out to have a mysterious, eroded surface, perhaps produced by the escape of carbon dioxide from the ices on its surface. Spectral measurements show deposits of carbon dioxide trapped in the ice and a dark, non-ice surface material probably rich in hydrocarbons and carbon-nitrogen compounds. Io, the acknowledged star of the *Voyager* show, also held surprises. Despite the satellite's yellow, sulfur-rich hues, temperature measurements of active volcanic eruptions proved that Io's volcanic engine is fueled by molten rock, not sulfur, even hotter than any that erupted on Earth since early in its history.

Galileo's crowning achievement for the moons is undoubtedly the information it gathered on what lies beneath their outer surfaces. Gravity data tell us that Io, Europa, and Ganymede all have dense, iron-rich cores, whereas intriguing Callisto is only partially differentiated, with an ice-rich outer layer but no dense core. Spectacular images of Europa's icy, fractured surface show a geologically young landscape with many regions resembling broken rafts of ice in Earth's arctic seas. Magnetic data suggest that not only Europa but Ganymede and Callisto as well have global, electrically conducting layers best explained by salty water in vast

e for the spacecraft Galileo*'s suicide plunge into*
d space of The Planetary Report*, we could cover all*
n. Its scientific investigations began while the spacecraft
s (and twice by Earth), encounters with asteroids Gaspra
comet Shoemaker-Levy 9 crashing into Jupiter. Then, it
5. Galileo *then released its probe into Jupiter's massive,*
net. Before its mission was complete, the spacecraft would
atellites, Io, Europa, Ganymede, and Callisto.
ing out of propellant to operate its thrusters, which mis-
, the spacecraft might have crashed into one of the large
hat might support life. So Galileo *was targeted to plunge*
l and burned to its constituent elements.
spectacular mission? We chose to let the mission scien-
ty's friends on the science teams to contribute their
ctive fields. Below, then, are what could be called the
luctive scientific explorations in history—the Galileo

subsurface oceans. Europa's 100-kilometer (62-mile) -thick water layer contains twice the amount of water as in all of Earth's oceans.

The *Galileo* mission's discoveries about the satellites have revolutionized views of the Jupiter system, the evolution of satellites, and the location of environments that potentially harbor life. They have captured the imagination of both the public and the scientific community, laying the foundation for future voyages of discovery to the outer reaches of our solar system.

Mike Belton of Belton Space Exploration Initiatives served as Imaging Science Team leader for the Galileo *mission. Although the spacecraft was designed to explore giant Jupiter and its largest moons, the mission gave Mike the opportunity to study one of his special interests—comets and their close relatives, asteroids.*

Galileo's "Eyes"

by Michael J.S. Belton

Asking the leader of the Imaging Science Team to choose the most significant discovery made by *Galileo* images is a tall order. Sure, I have my own opinion—my team's discovery of a thin, ruptured, possibly mobile, and geologically young ice shell over the deep global ocean that must exist on Europa, as indicated by *Galileo* gravity and magnetic measurements. But this probably is a controversial choice within the team, for there were many fascinating discoveries made, and the significance of these discoveries depends very much on what you think is of fundamental importance.

For me, the Europa discovery definitively exploded old ideas of where habitats of life might exist in the planetary systems that must abound in the galaxy. It placed Europa high on, if not at the top of, the list of targets for detailed exploration in the United States' program of space exploration.

Volcanism is a reality, and to some an ever-present danger, on Earth. On Io, where volcanism is ubiquitous, we discovered that very high temperature volcanism, similar to activity that occurred on Earth in the geologic past, is widespread. This connection with Earth's volcanic history makes it a highly significant discovery and a priority to be pursued in future exploratory missions.

The imaging team's success in discovering and following the nature of the initial impulse of the radiation liberated when a comet fragment hypersonically collides with a planetary atmosphere, a comet Shoemaker-Levy 9 event, is also on the list. Here the images were part of a campaign made up of many experiments that together have had, at least in my opinion, a highly significant influence on the way people view cosmic impacts with the Earth and their determination to do something about them.

The dozen or so people who make up the imaging team reflect interests from all parts of planetary science, and the investigations that were pursued covered a broad spectrum. They brought forth discoveries ranging from phenomena involving fine dust in Jupiter's rings to the surface expressions of a deep ocean on Europa; from glowing plasma in Io's dynamic atmosphere to superheated lavas overflowing, and gigantic plumes exploding, from fiery lakes; from the origins of gigantic frozen impact basins to the origins of mountains, one at least 16 kilometers (10 miles) high; and from swirling clouds and gases that could engulf objects the size of the Earth to delicate aurorae high above. This list presents only some of what was addressed at Jupiter.

And here I am asked to choose the MOST significant discovery! It's not that easy: in *Galileo* imaging, there were just too many successes.

The Near Infrared Mapping Spectrometer (NIMS) on Galileo *enabled us to see, in a different light, the atmospheres of Venus, Earth, and Jupiter, as well as the surfaces of two asteroids and the four Galilean moons. Bob Carlson of the Jet Propulsion Laboratory led the NIMS teams through the 14 years of the* Galileo *mission.*

14 Exciting Years for the Near Infrared Mapping Spectrometer

by Robert W. Carlson

Galileo's roundabout journey in the solar system and its orbital tour around Jupiter have been a thrilling trip for those involved with the Near Infrared Mapping Spectrometer (NIMS). The spectacular launch was soon followed by gloom and anxiety when our protective cover failed to eject. But after a week of cliff-hanging suspense, the cover was ejected successfully, just in time for the Venus flyby. Our new planetary science capability—infrared imaging spectroscopy—rewarded us with intriguing new views of Venus.

The Earth flybys provided an opportunity for an unusual experiment. The late Carl Sagan wanted to investigate the ability of modern planetary spacecraft to detect life, suggesting a control experiment using *Galileo* to look for life on Earth! NIMS indeed found chemical evidence for terrestrial life from the extreme disequilibrium presence of methane (biogenically produced) in an oxygen atmosphere, an obvious but gratifying result.

Our solar system tour included two asteroid encounters, and NIMS, in collaboration with the Solid State Imaging (SSI) experiment, found that one of these asteroids, Ida, had a moon. Although the presence of moons around asteroids had been suggested, these notions generally were considered preposterous, so finding Dactyl (as the moon was named by the teams' discoverers) was an exhilarating surprise.

By great good luck, *Galileo* could directly observe the collision of comet Shoemaker-Levy 9 with Jupiter, an event invisible from Earth. The infrared light curve obtained by NIMS yielded the temperature and size history of the plume and the diameter of the impactor. It was great fun analyzing these data and painting a mental picture of this awe-inspiring event.

During the orbital mission, NIMS investigated Jupiter's atmosphere, especially water vapor in the deep atmosphere and, with SSI, its association with moist convection and lightning in Jupiter's belts. NIMS also discovered fresh ammonia clouds in Jupiter's atmosphere, the first time that an unambiguous spectral signature of ammonia (NH_3) ice was observed from any planet. It is still a mystery why only fresh clouds, covering only 1 percent of Jupiter, show the ammonia signature, whereas the remaining upper clouds, probably containing NH_3, lose their sharp spectral features.

The temperature of the lavas from Io's volcanoes can be higher than that of any current terrestrial volcanoes and may be similar to those of ultramafic lavas (rich in magnesium) that erupted on Earth billions of years ago. We have identified long lava flows, violent eruptions generating large plumes, and extensive lava lakes. Some Ionian plumes are generated by the interaction of a moving lava flow with the underlying sulfur dioxide snowfield, so the plumes move with the flow fronts. Prometheus, the "wandering volcano," is an example.

The outer icy satellites are equally interesting. Europa's surface was found to be profoundly modified by energetic particle bombardment from Jupiter's powerful magnetosphere, producing bizarre surface chemical compounds such as hydrogen peroxide and sulfuric acid. The time scale for this radiolytic modification is surprisingly short—only tens to hundreds of years. Minerals from a subsurface ocean may be present on the surface as well, but they probably have been modified by radiation. All three icy satellites show carbon dioxide in their surfaces, and Callisto has a tenuous carbon dioxide atmosphere.

Galileo's tour of the solar system and around Jupiter was scientifically exciting and fruitful; thanks to the NIMS team, it also was a fantastic personal adventure. *Galileo* has been part of our lives for many years and it fittingly will become part of Jupiter.

Andy Ingersoll, the Earle C. Anthony Professor of Planetary Science at the California Institute of Technology, has spent most of his professional life learning how planetary atmospheres work. The Galileo *probe and the orbiter's imaging systems returned data that have enabled him to study even more deeply the atmospheric dynamics of the biggest planet in our solar system.*

Jupiter's Atmosphere from *Galileo*

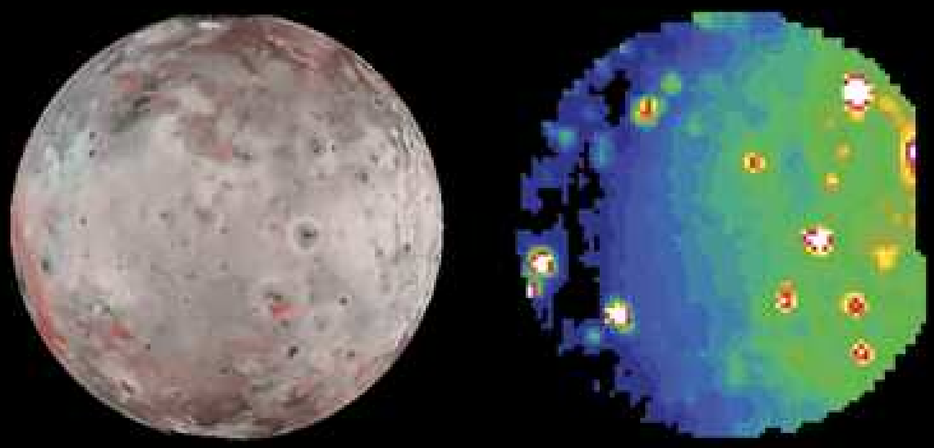
by Andrew P. Ingersoll

Some of the objectives for the *Galileo* probe and orbiter were to measure water, winds, clouds, lightning, and auroras. There were problems, but the discoveries were spectacular.

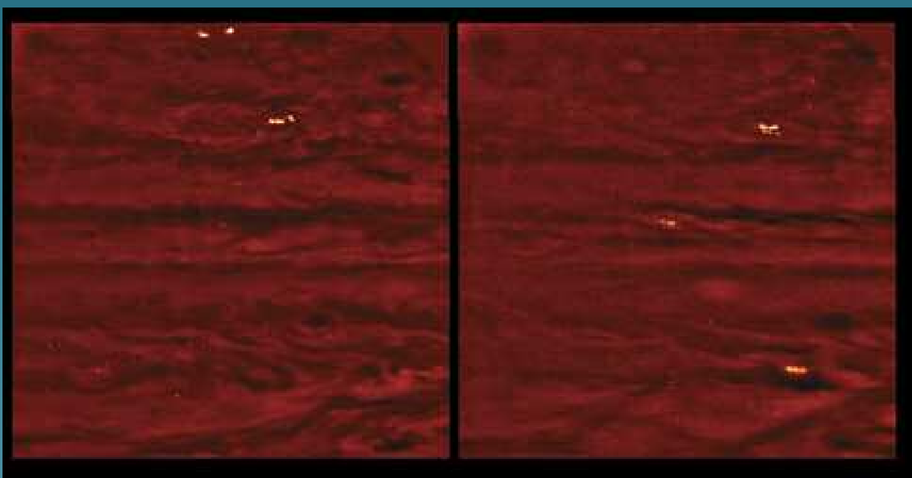
On Earth, the water cycle accounts for most of the heat transfer from ocean to atmosphere. The water goes up as vapor and comes down as solid or liquid, thereby using its latent heat of vaporization to move energy . The same process occurs on Jupiter, except there is no ocean. Instead, there is a deep atmosphere, with a given global amount of water vapor, that is heated from below by the planet's interior. Depending on the water abundance, the base of the water cloud was calculated to lie between 5 and 7 bars (five to seven times the sea-level pressure on Earth).

The *Galileo* probe's last transmission was from 22 bars, which was deeper than the probe was designed to go, but the water vapor abundance relative to the principal constituent hydrogen (H_2) was still increasing with depth. So even at this depth, the base of the water cloud had not been reached. The problem seems to be that the probe hit a dry spot, as evidenced by the relative lack of clouds at the probe site. As on Earth, the dryness probably was due to downwelling of air that had lost its volatiles by precipitation.

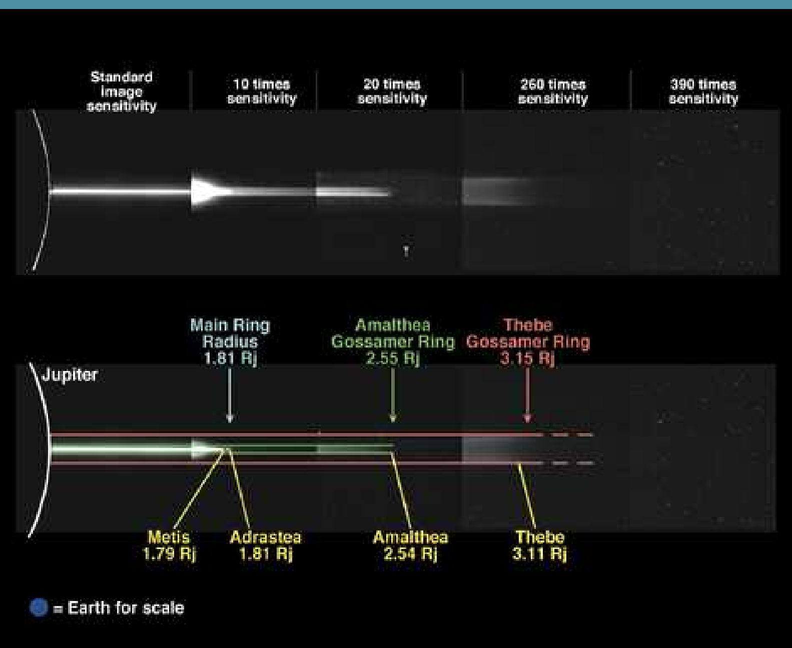
The special nature of the probe site complicated the interpretation of wind speed. From tracking clouds at the 0.5 to 1.0 bar level, we knew that the wind there was approximately 100 meters per second (about 225 miles per hour) relative to the planetary interior. From the Doppler shift of the probe's radio signal, the *Galileo* scientists found that the winds increased with



BOB CARLSON: *Prior to* Galileo*'s arriving at Jupiter, we had speculated on whether we would see a volcanic outburst on Io and feared that we might not. Our worries were needless; Io was found to have about 150 volcanoes! Some of these were explosive and episodic, while others were steady and persistent. The Near Infrared Mapping Spectrometer (NIMS) image on the right shows infrared thermal emissions from more than a dozen active volcanoes. These volcanoes generally correlate with the dark spots visible in the Solid State Imaging view at left.*



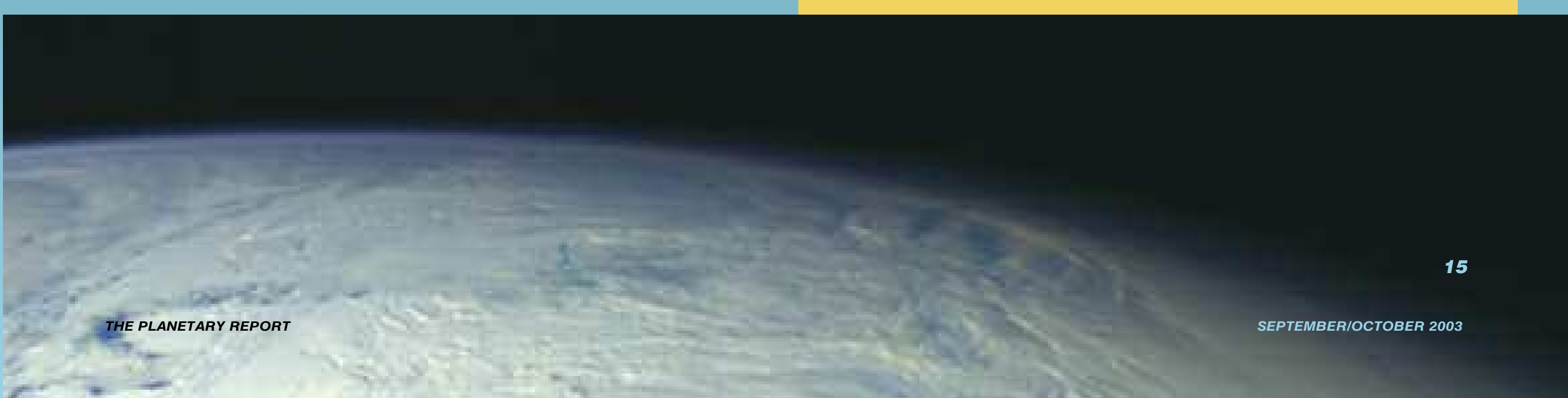
ANDY INGERSOLL: *My favorite* Galileo *image is one of lightning in the moonlit clouds of Jupiter. The idea of Io illuminating the clouds on the night side did not occur to us until we discovered it by accident. These two images, taken in visible light and shown in shades of red, reveal lightning storms on the night side of Jupiter. The lightning results were important for the study of Jupiter's atmospheric dynamics. Besides, they're pretty pictures.*



MIKE BELTON: *A small subset of the* Galileo *images stand out for the inventive virtuosity of the team members who planned them. Because of technical difficulties that the pictures posed, nearly all of them are available only in black and white, are of moderate resolution, and are sometimes smeared. To me, however, because of the significance of the discoveries made with them, they are as spectacular as those of the most seductive color and highest resolution.*

My absolute favorite is this mosaic of the Jupiter ring system. When I first saw the pictures in it, my response was "Nice try, but hopelessly smeared!" But this was not a smear—this was our first view of a structured gossamer ring. These pictures took the rings from the realm of mystery to a textbook case of a clearly understood phenomenon.

LOUIS D. FRIEDMAN: *This mosaic of Earth's limb looking north past Antarctica reminds me that* Galileo *was the first spacecraft to approach Earth from another planet. To an old celestial mechanics analyst, that was a great—and very symbolic—event. The Planetary Society organized a special symposium for the occasion, featuring our then-President, Carl Sagan. His speculations about the spacecraft discovering the first signs of life as it approached Earth were a joy. I also liked the idea that Earth gave* Galileo *a "gravity assist." It caused an imperceptible slowing of our planet in its orbit, but I dare say no one has noticed the shorter year.* *All images: JPL/NASA*



depth and then leveled off at 180 meters per second below 5 bars. Although this favors the "deep wind" model of Jupiter's atmosphere, the fact that the water abundance had not reached its final value means that the winds might not have reached theirs either.

Cameras on the orbiter caught lightning flashes on the night side and were able to match them with small storm clouds on the day side. The size of the bright spots at cloud top level indicates that the electrical discharges are deep, probably occurring near the base of the water cloud. The orbiter saw traces of water vapor and water ice clouds through holes in the high-level clouds of ammonia (NH_3) and hydrogen sulfate (H_2S). There is evidence that the storm clusters provide energy for the multiple jet streams and large ovals like the Great Red Spot by merging with them. The cameras imaged the Jovian aurora on the night side and determined its altitude, which tells where energetic particles are being absorbed.

Toby Owen, of the Institute for Astronomy at the University of Hawaii, studies the origin and evolution of atmospheres on both planets and satellites. The probe that Galileo *shot into Jupiter provided the first in-situ measurements from a giant planet's atmosphere, and Toby was privileged to be part of the team that analyzed the results.*

The *Galileo* Probe—A Chemistry Lesson

by Tobias Owen

As is true for the Sun and most other stars, more than 90 percent of the mass of Jupiter consists of just two elements, hydrogen and helium. The probe measured the mass fraction of helium in Jupiter's atmosphere with a mass spectrometer and a dedicated interferometer. The results were identical: 23.4 percent of the mass of the atmosphere is contributed by helium. This is slightly smaller than the original mass fraction of helium that Jupiter must have had at the time of its origin, as deduced from studies of the Sun. The depletion in Jupiter's atmosphere is understood to result from the steady precipitation of helium "raindrops" deep in the planet's interior, as helium comes out of solution in the fluid metallic hydrogen that makes up most of Jupiter's mass. Neon evidently dissolves in the helium raindrops, because it is even more depleted in the atmosphere than is helium.

Neon, argon, krypton, xenon, and hydrogen sulfide were detected for the first time by the probe's mass spectrometer, which also determined isotope ratios. Combined with measurements of methane and ammonia, these new detections revealed that, relative to hydrogen, all the elements besides helium and neon are enriched by a factor of about three in Jupiter's atmosphere, compared with abundances in the Sun.

The enrichment of carbon had been known from *Voyager* and Earth-based studies of methane and was thought to have resulted from the delivery of heavy elements by comet-like icy planetesimals that built the planet's solid core and enriched the forming envelope during the epoch of Jupiter's formation. The excess nitrogen and argon were a complete surprise, because comets are deficient in these two elements.

We are still missing the crucially important abundance of oxygen, whose dominant carrier on Jupiter is water. The water abundance is limited by the local temperature above the level in the atmosphere where water vapor condenses. Because the probe entered the atmosphere over a local "hot spot" where condensable volatiles were dramatically depleted, the temperature at which the instrument electronics failed was reached before the probe penetrated below the condensation level, where water vapor would have been fully mixed. Even without the oxygen abundance, however, we can draw two important conclusions.

First, the *Galileo* probe results appear to require the presence of a new kind of icy planetesimal in the early solar system, one that was formed at temperatures below 30 degrees Kelvin to capture argon and N_2, the dominant carrier of nitrogen. Some of these planetesimals may still be with us, lurking in the Kuiper belt or the Oort cloud. If so, we will recognize them by their solar abundances of nitrogen and argon relative to those of other heavy elements such as carbon.

Second, the observed enrichment of heavy elements offers a new constraint that models of Jupiter's formation must satisfy. It implies an abundance of 18 Earth masses of heavy elements in the planet. Although such an enrichment seems plausible with models involving early accretion of planetesimals, it is less obvious how formation from an instability in the nebula could achieve it.

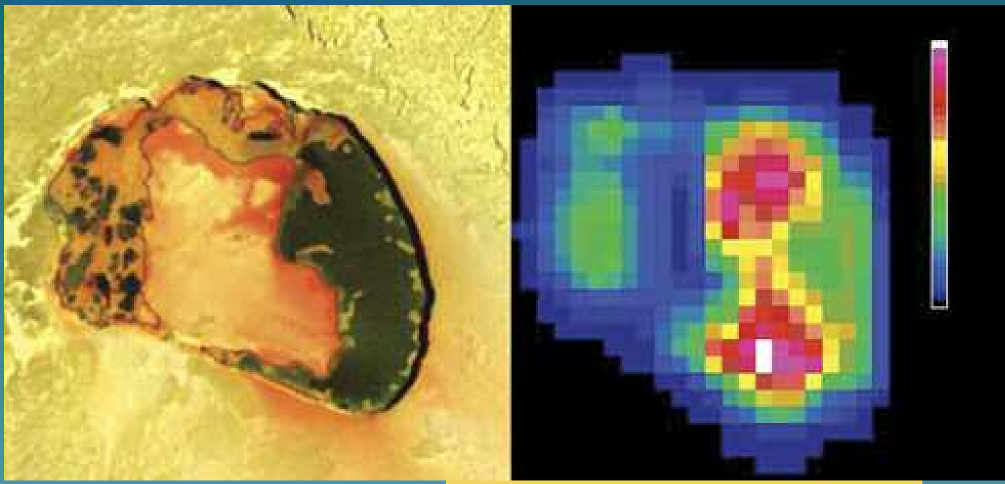
The magnetometer on Galileo *picked up signals indicating that three of Jupiter's moons probably possess salty oceans beneath their icy crusts. Margaret Kivelson, professor of space physics at the University of California, Los Angeles, led the team that finally received the attention it deserved.*

Magnetic Structures of the Galilean Moons

by Margaret Kivelson

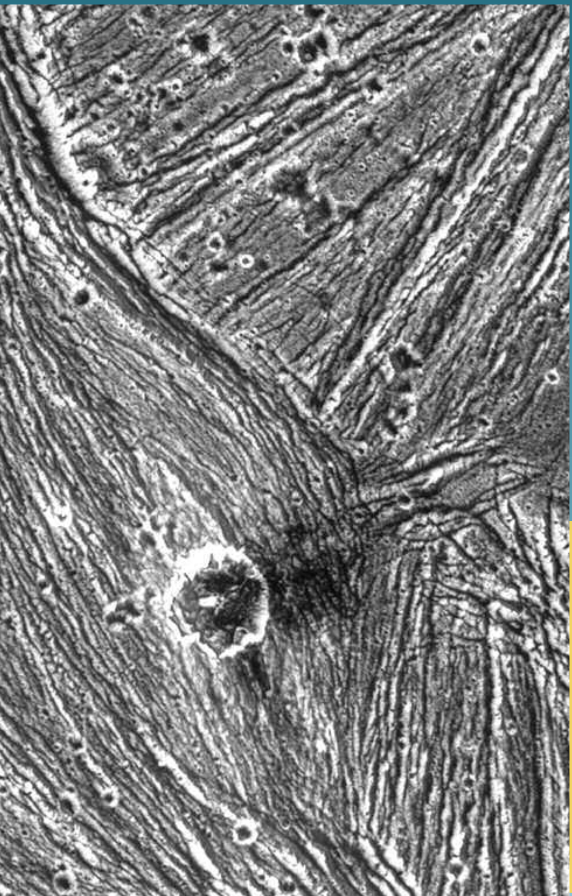
It was almost 14 years ago on Cape Canaveral that members of the *Galileo* Magnetometer Team watched a space shuttle lift off the ground and start *Galileo* on its long and convoluted journey to Jupiter. As we dreamed of what we would learn about Jupiter and its moons, we had a clear sense of the vast size and

TORRENCE JOHNSON: *This picture of ice rafts on Europa is probably my favorite from the mission. It's not of the highest resolution or the only image of the chaos terrain, but it represents the point at which we first saw features on Europa's surface that clearly indicated the possibility of a subsurface ocean. It also illustrates the changes, since* Voyager*, in the way we deal with data. When this image came in, there was no photogenic scene of scientists jumping up and down in front of a monitor. Instead, there was an instantaneous explosion of e-mail from our far-flung imaging team, all with the same message: "GO LOOK AT THIS PICTURE!"*



ROSALY LOPES: *Io's Tupan Caldera was one of the first new active volcanoes that I discovered using* Galileo's *NIMS in 1996. (The NIMS image is shown here to the right of a visible light image, for geographical context.) The caldera was named, at my suggestion, after the Brazilian god of thunder—a way of honoring the country in which I was born. Tupan is one of the several volcanoes on Io that we interpret as lava lakes. These volcanoes appear to be long-lived (perhaps for decades), making them similar to some lava lakes on Earth such as those observed at Hawaiian volcanoes.*

All images: JPL/NASA



JOHN CASANI: *When the first images of Ganymede came in, the science guys invited me to come into their area and very proudly showed me a picture of the surface terrain of Ganymede. Compared with what we had seen with* Voyager*, the resolution and the detail blew me away. Realizing what we had been talking about and what we had been promised in terms of resolution—and then actually seeing it—that was what got me. That was the moment.*

the magnetic structure of the magnetosphere that surrounds the planet. We also knew that strong currents are present in the plasma near Io and that these currents flow from Io into Jupiter's magnetosphere, where they generate intense radio frequency waves. We knew nothing about the electromagnetic signatures present near the other large moons of Jupiter.

Once *Galileo* was in orbit around Jupiter, we found that the magnetosphere is often dynamic on large scales, and that magnetic activity correlates with particle acceleration processes and plasma wave activity, mimicking in some ways features that are observed at geomagnetically active times on Earth. However, to understand fully the differences in the dynamic responses between Earth and Jupiter, we needed to acquire data from a large range of distances from Jupiter and to cover a large range of angles relative to the Jupiter-Sun line. After nine years of *Galileo* being in orbit around Jupiter, we have finally completed the required coverage.

As we work to extract a coherent picture of the spatial structure and temporal variations of the magnetosphere, our team is still arguing about the source of the disturbances. Some think they arise from changing properties of the solar wind, whereas others think they are often generated by the slingshot effect of the planet's rotation. Because scientists love a mystery, the "discovery" that the magnetosphere is too complex to be understood without a great deal of additional work is in itself exciting.

Still more exciting are the measurements that we have been able to understand unambiguously and interpret convincingly. Of these discoveries, the most memorable were those that revealed internal properties of several of the moons. First we found that Ganymede has a substantial magnetic dipole moment, larger than that of Mercury. The thrill of our first look at the plot of field strength versus time as *Galileo* passed by Ganymede, a plot that revealed the presence of the internal field, is decidedly unforgettable. The internal field gives insight into properties of the moon's interior. In particular, Ganymede must have a deeply buried, fluid, and metallic outer core. Io, on the other hand, does not have an internal magnetic moment, despite the presence of fluid material that appears in the volcanoes at the surface.

High up on the scale of exciting discoveries comes the evidence that the icy moons—Europa, Callisto, and Ganymede—possess time-varying internal magnetic moments. (A time-varying moment is the signature of electromagnetic induction in a conducting shell.) The moments observed were sufficiently large that we were able to assert that the currents generating them flow not far below the surfaces, in layers embedded within the icy crusts. The most likely conductor is water containing electrolytes, a situation that lends itself to dramatic speculation.

Rosaly Lopes received her PhD from London University in 1979, the year that the Voyager *spacecraft encountered Jupiter and discovered erupted volcanoes on its moon Io. It's hard to imagine a more exciting finding for a newly minted volcanologist, and Rosaly soon found herself at the Jet Propulsion Laboratory as a member of the Near Infrared Mapping Spectrometer science team.*

Io's Active Volcanoes

Rosaly Lopes

Active volcanism on Io was discovered by *Voyager* in 1979, but *Galileo* revealed many new surprises. *Voyager* had detected about a dozen active volcanoes, and more had been detected from Earth. We expected to find a few more from *Galileo* observations but were surprised to find more than 100 new ones.We now know that Io has at least 152 active volcanoes, 104 of which were found or confirmed by *Galileo*'s observations.

One surprise was the temperature of the lavas. *Voyager* instruments detected relatively low temperatures for the erupted material, which led many scientists to believe that Io's volcanoes erupted sulfur rather than basalts and other silicates. Our biggest surprise was finding out that at least one of the volcanoes, and maybe all of them, erupts lavas that are hotter than any we know on Earth today. The Ionian lavas may be similar to ultramafic-type lavas that erupted on Earth billions of years ago, thus giving us a "window" into Earth's volcanic past.

Galileo was the first spacecraft to make close flybys of Io's surface, taking "close-up" images of the volcanoes. We have identified long lava flows, violent eruptions generating large plumes and lava lakes. *Galileo* discovered Io's tallest plume, which reached some 500 kilometers (320 miles) in height, during a close flyby in August 2001. It erupted from a previously unknown hot spot that suddenly became active. I remember how my imaging team colleagues were puzzled trying to figure out where the plume was coming from until the infrared image I was working on showed me a huge thermal emission from a location we had never before seen active. What was most exciting was that *Galileo* had flown into this plume and come out undamaged.

In spite of Io's rampant volcanism, about 90 percent of the surface remained unchanged between the *Voyager* observations and those of *Galileo*. This was a surprise, as observations from Earth and the Hubble Space Telescope prior to *Galileo*'s arrival led us to think that the surface might have been largely changed since *Voyager*. Some even said we would not recognize it. But Io is full of puzzles and contradictions, and I have no doubt that future missions will find many surprises for us. ❍

World Watch

by Louis D. Friedman

Washington, DC—Congress attacks Pluto again! In a surprise move, during the week before the US House of Representatives adjourned for the summer break, it passed a NASA appropriations bill that deleted $55 million from the New Frontiers program. If that cut is affirmed in final congressional action, the first mission of the program—the *New Horizons* mission to Pluto and the Kuiper belt—will be delayed at least one year.

That will delay the spacecraft's arrival at Pluto by at least three years. The later launch will require it to travel on a slower trajectory and will eliminate a gravity assist from Jupiter that would slingshot the spacecraft and speed it on its way.

Ironically, the bill that cuts New Frontiers gives NASA slightly more funding than President Bush requested in his budget. The bill is loaded with items inserted by individual representatives to benefit their districts. These so-called earmarks are a mix of pet projects, some clearly "pork" and others worthy science projects that NASA or the Bush administration declined to present in their budgets.

The fate of *New Horizons*, as well as other cuts proposed by the House, depends on the complex and secretive conference process in Congress. This fall, the Senate Appropriations Committee will act, producing its own version of the budget, which then will be voted on by the full Senate. Then the House and Senate committees will resolve their differences in a conference. Typically, that is where the final decisions are made.

This year's tough decisions will be made tougher by consideration of the *Columbia* Accident Investigation Board findings. Not only will NASA need money to get the existing space shuttles flying again, but Congress also is expected to debate the future of human space transportation. Its choice is whether to initiate development of a new vehicle to replace the shuttle or instead to extend the operational lifetime of the current fleet for another decade or more. Money to fund either decision could be taken from other elements of the NASA program, such as New Frontiers, Prometheus (the nuclear space initiative with a Europa orbiter as its first application; see page 11), or the Mars program.

For the remainder of this year, forestalling raids on the space science and exploration budget will be an important objective of The Planetary Society's political actions.

As we go to press, the *New Horizons* mission to Pluto and the Kuiper belt is in danger of being delayed or even canceled. For years, The Planetary Society has led the fight for this mission, and three times we have garnered enough congressional support to save it. Last year, we had hopes that the fight was finally over. Now, it appears we may have to mobilize support again.

The congressional conference process that will decide its fate is rapid and conducted mostly behind closed doors; we can't say exactly how this issue will come to a decision. Please watch our website, *www.planetary.org*, for up-to-date information and our recommendations for action.

No matter what the nature of congressional maneuvering, Planetary Society members in the United States can and should write their senators and representatives and tell them that they support planetary exploration. Ask them to support the *New Horizons* mission, the New Frontiers program, Mars exploration, and the entire space science endeavor. To locate the names and addresses, fax numbers, and e-mail addresses of your congresspeople, please visit *www.planetary.org* and follow the links in the "Taking Action" section.

Tucson, AZ—NASA has selected *Phoenix*, a Mars lander, as the first mission in the new Scout program. Scouts are Mars missions proposed and led by scientists. The winning proposal was spearheaded by University of Arizona scientist Peter Smith and included teams from the Jet Propulsion Laboratory and Lockheed Martin Space Systems.

Phoenix is based on the 2001 lander mission that was canceled after the failures of *Mars Climate Orbiter* and *Polar Lander* in 1999. It will use hardware that was built for the 2001 mission.

Phoenix will land in the high northern latitudes of Mars, in terrain that might be as much as 80 percent water ice by volume, with that water lying less than 1 meter below the surface. It will make the first subsurface analysis of ice-bearing materials on another planet. The mission includes an innovative camera system and a robotic arm capable of digging into Mars' surface.

The lander mission beat out three other finalists in the competition (out of an original 23 proposals): an orbiter, an atmosphere sample return, and an airplane.

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

Society News

Celebrating *Galileo*

As we went to press, we had a great turnout at our special tribute to the *Galileo* spacecraft and its team: a one-time dramatic reading titled "An Evening with Galileo and His Daughter," on September 22 at the Pasadena Playhouse.

In honor of the 14-year mission, the Society asked author Dava Sobel to create a dramatic reading from her best-selling book, *Galileo's Daughter*. John Rhys-Davies and Linda Purl took the stage at the Pasadena Playhouse under the direction of Robert Picardo, actor and member of the Society's Advisory Council. The script is based on actual letters between father and daughter, as well as on Galileo's first-person narrative about his momentous discoveries.

The Planetary Society also honored the *Galileo* mission team with a special award at the event.

—Susan Lendroth, Manager of Events and Communications

Birthday Wishes for Ray Bradbury

The Planetary Society celebrated the 83rd birthday of Ray Bradbury, one of the greatest science fiction writers of all time and a member of the Society's Advisory Council, in a two-part event on August 23. Friends and well-wishers gathered at Society Headquarters in Pasadena to hear tributes to the author, then moved to Mt. Wilson Observatory in the Angeles National Forest for the rare opportunity to view Mars through the 60-inch telescope.

The Planetary Society gathered more than 6,000 greetings from people around the world, which were presented to Mr. Bradbury in a special card at the party. Birthday sentiments sent to Ray Bradbury included those of motion picture director James Cameron and *Apollo 11* astronaut Buzz Aldrin. Among the guests for the evening were motion picture director Peter Hyam, actress Angie Dickinson, and members of the press.

The celebration took place just days before Mars Day on August 27, when Mars was at its closest approach to Earth in more than 50,000 years. The Planetary Society has taken the lead in a global campaign to encourage the world's population to observe Mars during this once-in-a-lifetime close approach.

—Linda Kelly,
Program Development Manager

Your Gift Matters

Your gift, whether it is $5 or $50,000, is crucial to helping The Planetary Society achieve its mission.

Your gifts help in a number of ways, from supporting our advocacy efforts to making the solar sail mission a reality, to forwarding the Search for Extraterrestrial Intelligence, to taking humanity one step closer to Mars as an official part of NASA's Mars Exploration Rover mission. Your support keeps our activities around the world active and vital.

We want you to support our mission by making gifts in the way that is most meaningful to you. You can create an endowed fund, honor or memorialize someone you love, have your company match your gift, create a planned gift to benefit the Society, or become a member of our Discovery Team or the New Millennium Committee.

You can learn more about funding opportunities at *http://planetary.org*, or contact Andrea Carroll at (626) 793-5100, extension 214 or *andrea.carroll@planetary.org*.

—Andrea Carroll,
Director of Development

The Planetary Society 2004 Catalog

Deep Space Mysteries: 2004 Wall Calendar

Each month, enjoy awe-inspiring, full-color images from deep space. This 2004 wall calendar is produced by the creators of *Astronomy* magazine. 2 lb. **#520 $12.00**

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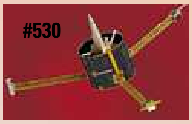

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Mini Mars Polar Lander Science Kit

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#778 $3.00

Cosmos 1 Team Jacket

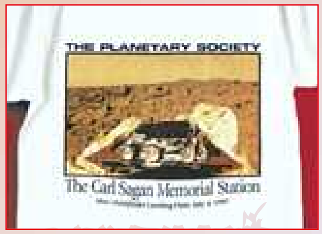
Planetary Society Members are an essential part of the *Cosmos 1* team! Get your official team jacket only through The Planetary Society. These water-resistant jackets are cobalt blue with "*Cosmos 1* Team" embroidered on the front and logos for The Planetary Society, Cosmos Studios, and Russian space agencies printed on the back. Special order only (allow 6–8 weeks for delivery).
Adult sizes: M, L, XL
1 lb. **#573 $60.00**

Cosmos 1 T-Shirt

The Planetary Society's *Cosmos 1*, the first-ever solar sail, will take off into orbit this year. This commemorative T-shirt is a Society exclusive. Long-sleeved, with glow-in-the-dark ink, it's perfect for dark nights of solar sail watching. Adult sizes: S, M, L, XL, XXL 1 lb.
#570 $25.00

"Is Anyone Out There?" T-Shirt

As we gaze out at the heavens toward a vibrant spiral galaxy, the question arises, "Is anyone out there?" This dramatic T-shirt captures the feeling of wonder when pondering our place in the universe. Adult sizes: S, M, L, XL, XXL
1 lb. **#586 $19.95**



Carl Sagan Memorial Station T-Shirt

This T-shirt displays the triumph of *Mars Pathfinder's* July 4, 1997 landing with a color image of the undeployed rover on the Carl Sagan Memorial Station.
Adult sizes: M, L, XL, XXL
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Future Martian T-Shirt

The future is full of possibilities, and today's Earth child just might be a future Martian.
Child sizes: S, M, L
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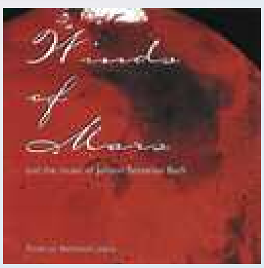
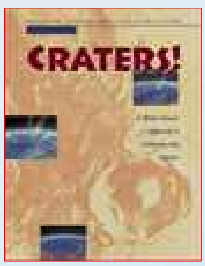


Winds of Mars and the Music of Johann Sebastian Bach

This audio CD features digitally simulated sounds of the winds of Mars heard between 17 of Bach's finest compositions, played on piano. Liner notes explain the production of the Martian sounds and offer a general history of Mars exploration. 1 lb. **#785 $15.00**



Craters! A Multi-Science Approach to Cratering and Impacts

By William K. Hartmann with Joe Cain. Produced by The Planetary Society and the National Science Teachers Association, *Craters!* explains how comets and volcanoes have affected Earth's history. It also includes 20 ready-to-use, hands-on activities and a CD-ROM (Windows and Macintosh compatible) filled with more than 200 images. For grades 9–12.
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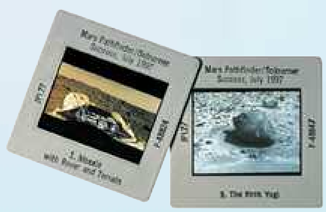

Pathfinder Images of Mars

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1 lb. **#215 $7.50**

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Pale Blue Dot Poster
In February 1990, *Voyager 1* looked back at its home planet for the last time. The image of Earth as a tiny bluish dot inspired Carl Sagan to write one of his best-known essays, which starts off his book *Pale Blue Dot*. The poster features Carl's timeless words and the full frame of the profound image captured by *Voyager 1*.
12" x 30" **1 lb. #326 $10.00**

Mars in 3D Poster
Put on your red/blue glasses and step onto the Martian surface where *Mars Pathfinder* still rests today. Red/blue glasses included.
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Panoramic View of Mars
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This astounding image, obtained by the Two Micron All Sky Survey, reveals only a fraction of the 400 billion stars in our own Milky Way galaxy.
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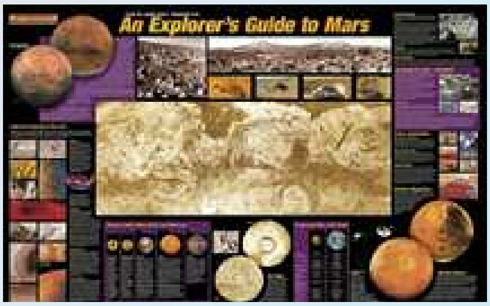

An Explorer's Guide to Mars
Images from *Mars Global Surveyor*, speculative paintings of the Red Planet's past and future, informative captions and charts, and images of Mars' surface from the *Pathfinder* and *Viking* spacecraft enhance a detailed US Geological Survey map.
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Attention, teachers—submit your order on your school letterhead and receive a 20% discount.

By the spring of 1609, simple 3-power telescopes were available in France and Italy, but it was the astronomer Galileo Galilei who made the instrument famous. In August 1609 he presented a 3-power telescope to the Venetian Senate, and in the fall of that year he turned a 20-power instrument toward the heavens. With this telescope, he observed the Moon and discovered Jupiter's four major satellites—which we still call "the Galilean Moons." *Galileo Presents His Telescope to the Doge in Venice*, by Luigi Sabatelli, is a fresco on the ceiling of the Tribuna di Galileo in Florence's Museum of the History of Science.

Luigi Sabatelli was born in Florence, Italy in 1772. In addition to his talents as a painter, he was a printmaker and draftsman. He died in Milan in 1850.

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