The PLANETARY REPORT

Volume XIV Number 5 September/October 1994

Clementine Maps the Moon

On the Cover:

The Moon has long been a proving ground for spacecraft from its nearby planet. The latest to visit was *Clementine*, the "smaller, cheaper, faster" mission launched by the Ballistic Missile Defense Organization. *Clementine* completely mapped the surface of the Moon, and this mosaic was made from the data collected of the Aristarchus plateau. Named for the large, bright Aristarchus crater, the plateau was probably uplifted, tilted and fractured by the giant impact that formed the Imbrium basin. Data like these from *Clementine* are helping fill out scientists' understanding of the Moon's history.

Image: Naval Research Laboratory
Processing: United States Geological Survey, Flagstaff

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From The Editor

Two recent programs supported by Planetary Society members have deeply affected the futures of both the American and Russian space programs.

As you may remember, late last year we asked Society members to fund a study on ways the Russian space program could assist NASA in launching a mission to Pluto. You responded enthusiastically, and two specific proposals from that study—to launch with a *Proton* rocket and to add a small probe into Pluto—made their way into an agreement signed by the vice president of the United States and the prime minister of Russia.

About the same time, we held a workshop for innovators in Mars exploration to brainstorm ways the spacefaring nations could combine their efforts to produce a realistic, continuing spacecraft program. Those results closely mirror the new "Mars Together" study also endorsed by the two political leaders.

Neither of these accomplishments would have been possible without your support. Planetary exploration is moving forward again, and our members can take pride in their contributions. Let's keep up the momentum!

—*Charlene M. Anderson*

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Members' **Dialogue**

***Apollo's* Gift**

I found Carl Sagan's assessment of the *Apollo* program (see "The Gift of *Apollo*" in the May/June 1994 issue of *The Planetary Report*) to be both interesting and enlightening. I agree that it is important for us to remember the less than scientific and ethical reasons for its inception and implementation, and to hope that missions are never again conducted under such circumstances.

However, it is equally important to emphasize one of its most valuable contributions. *Apollo* proved conclusively that humans can exist, function and work on other worlds. Robotic emissaries, however valuable, will ultimately increase our species' natural urge to actually "go there" and see for ourselves. *Apollo* showed, beyond endless theory and conjecture, that environments much more hostile than Earth's are not entirely off-limits to us and that dreams shared by countless generations before us can be realized. Let us reflect on the mistakes of *Apollo,* so as never to revisit them, and, above all, let us honor its "greatest gift" of "opening the door" and letting us out—into the universe.

—ERICK WOODS,
Sebastopol, California

I rarely write letters to the editor, but I felt that the excellent May/June 1994 issue of *The Planetary Report* had to be the exception to the rule. There was such a wealth of important and interesting information—everything from "The Gift of *Apollo*" right through to the back cover painting. The layman-understandable language and terrific photos made it impossible to put this issue down.

—A.G. OTTEN,
Toronto, Ontario, Canada

Planetary Protection

Throughout your thought-provoking special issue on planetary protection (July/August 1994), I did not notice any mention of the bacteria that were retrieved from the *Surveyor 3*'s television camera following its return to Earth as part of the *Apollo 12* mission in November of 1969.

The bacteria were common terrestrial microorganisms that had apparently traveled to the Moon with *Surveyor 3* in April of 1967. They had survived in a dormant state for thirty-one months on the lunar surface, protected to some degree by *Surveyor*'s camera housing.

Because of the Moon's inhospitable environment, *Surveyor* spacecraft were decontaminated but not sterilized, since the general view at the time was that terrestrial microorganisms did not represent a significant threat to the lunar environment. But the hardy bacteria demonstrated their ability to survive despite their two-and-a-half-year exposure to the Moon's harsh conditions. It is a case worth remembering.

—WILLIAM F. MELLBERG,
Park Ridge, Illinois

I do not agree with Thomas Jukes' statement (see "Lessons From Evolution: Ruling Out Danger" in the July/August 1994 issue of *The Planetary Report*), "There is no reason to assume that martian organisms would use the same amino acids or genetic code as does terrestrial life." In fact, there are excellent reasons for believing that martian organisms, and many other organisms in the universe, will use the same amino acids and the same genetic code.

We do not yet know the reasons why our genetic code specifies the particular amino acids that it does, but when we do, surely we will find that the code is not arbitrary. We will find that the code specifies the amino acids it does for physicochemical reasons (for example, this acid fits this particular conformation of nucleotides), and since we believe that the same physical and chemical laws apply throughout the universe, it follows that the code will be the same. The real question is whether an alien organism uses a mechanism based on nucleotides, and if so, whether it uses the same nucleotides.

—ALFRED C. HEXTER,
Kensington, California

Faulty Logic?

The July/August issue contains an interesting error in logic. On the discovery of a satellite orbiting an asteroid (see Factinos on page 29), it states that "Having found one fairly quickly, we can say that they're probably more common than previously thought." This seems to imply a general rule that seen-on-the-first-try means commonplace.

Gallup makes thousands of telephone calls before stating any probability. If you consult the record of lottery winners, you will probably find a winner among the first-time players. This does not mean that that player has a high probability of winning in the future. When I first tried the random-number generator on my computer, it produced the series 39461. Since this series was obtained on the first try, does that mean that 39461 is more probable than we had thought? Is there something wrong with my computer?

If we have seen a satellite on the first try (or any other try), our response ought to be, "I wonder what the probability is."

—NORMAN I. COWAN,
Woodview, Ontario, Canada

Please send your letters to Members' Dialogue, The Planetary Society, 65 North Catalina Ave., Pasadena, CA 91106-2301.

To Pluto by

by Robert L. Staehle,
Richard J. Terrile and
Stacy S. Weinstein

In 1991, with *Voyager 2*'s Neptune encounter two years behind us, the United States Postal Service issued 10 stamps commemorating the success of planetary exploration. On stamps for each of the first eight planets and the Moon appeared an illustration of the celestial body with one of the spacecraft that visited it. On the stamp for Pluto were the words, "Not yet explored," as if to taunt engineers and scientists at Pasadena's Jet Propulsion Laboratory (JPL), where the stamps were unveiled in a first-day-of-issue ceremony on October 1.

That date marks the birth of an all-out effort to erase those taunting words and to do it with what may be the fastest object ever launched from Earth. What follows is the story, still unfolding, of the Pluto Fast Flyby, which we hope will culminate in a dual flyby of Pluto between 2007 and 2010—before Pluto's atmosphere collapses and its southern hemisphere falls into shadow for the next century. A few dozen people are leading the effort today from organizations scattered around the United States. We have many enthusiastic supporters, including NASA Administrator Dan Goldin. And we have a few detractors who question the speed with which we are proceeding, our ability to meet stringent cost targets, the value of visiting Pluto—or who just wish they were in our shoes.

We Are Not the First

Many in the science community have been pushing for the first reconnaissance of Pluto. In 1988–1989, an unofficial "mission interest group" was encouraged by Geoff Briggs, then NASA's head of solar system exploration. He asked members of the Discovery Program Working Group, including scientists Fran Bagenal, Bob Brown and Alan Stern, to study Pluto mission ideas with the help of another group member, trajectory designer Bob Farquhar (see the July/August 1990 *Planetary Report*). In 1989, trajectory engineer Stacy Weinstein collaborated with spacecraft systems expert Ross Jones at JPL on an idea for a five-to-six-year direct trip with a 39-kilogram (86-pound) microspacecraft. Not too many people paid attention to microspacecraft back then, and the idea received little attention.

The next year brought a new Pluto flyby idea. A design effort coordinated by Bob Farquhar (then at NASA headquarters in Washington, DC) called for a 350-kilogram (770-pound) spacecraft with a 45-kilogram (99-pound) science payload to be launched by a low-cost *Delta 2*. Although the spacecraft would have been much lighter than other planetary spacecraft—*Voyager,* for instance, weighed in at 815 kilograms (about 1,800 pounds)—the high energy needed to get to Pluto directly could not be supplied by the *Delta 2*, so the trajectory used Earth and Jupiter for gravity assists. Travel time to Pluto would have been 13.6 years, with launch opportunities from 2001 through 2003.

Yet another Pluto flyby concept appeared in 1991—the *Mariner Mark II* (*MMII*; now being built in the form of the *Cassini* mission to Saturn). Weighing over 2,000 kilograms (4,400 pounds) without propellant and costing over $2 billion, this Pluto flyby was to have had a daughter probe to see both sides of Pluto, a large science payload, and a flight time of 16 years. Launched by a *Titan 4/Centaur* rocket, it would have followed the same trajectory as the previously mentioned 350-kilogram spacecraft. With its sister mission, a Neptune orbiter, it would have gone into production just after the *MMIIs* were being launched for *Cassini* and the since-canceled Comet Rendezvous Asteroid Flyby. Many engineers and scientists felt strongly that mass, flight time and cost for an initial Pluto flyby were headed in the wrong direction. Stacy didn't enjoy the thought of trying to support a mission that wouldn't get to Pluto until 2017.

By the end of fiscal year 1991, any hope of a fast Pluto flyby looked pretty dim.

At about this time, technical manager Rob Staehle was working for Bob Easter, then head of cost engineering management systems, on ways to make JPL more efficient and cost-effective. On October 1, 1991, the day of the

Way of a Postage Stamp

postage-stamp unveiling, Rob stopped by friend Stacy's office with the Pluto stamp. He jokingly asked what was being done about this piece of unfinished business, "Pluto—Not yet explored." When the conversation got around to an idea of Rob's to do an orbiter mission, Stacy scoffed, explaining that Pluto's small mass wouldn't even start to slow the spacecraft down.

Undaunted, Rob suggested a microspacecraft with staged solid rocket motors. Stacy was still doubtful, especially since "no one ever pays attention to microspacecraft around here." At that point, Rob recounted a meeting at which he had been shown a 300-gram (10.5-ounce) attitude-control camera that fit in the palm of his hand—a "star wars" product of Lawrence Livermore National Laboratory. Incredulous, Stacy took a look at Rob's orbiter idea, and in a week and a half announced that a 35-kilogram craft could be placed in orbit around Pluto, but the flight time would be 18 years and keeping the solid rocket motors warm that long might be a problem. However, 18 years for an orbiter didn't look so bad next to a 16-year flyby.

The next step was to muster support from the JPL community. Moustafa Chahine, chief scientist at JPL, liked the idea and gave us his support, encouraging John Beckman, head of planetary advanced studies, and Charles Elachi, assistant laboratory director for space science and instruments, to fund a small proposal. For science support, we turned to planetary scientist Bob Brown and astronomer Rich Terrile, both members of the NASA-chartered Outer Planets Science Working Group (OPSWG), which had to endorse a project before it could proceed. Although Bob was busy with the *Cassini* mission, he was instrumental in helping us get early backing. Rich had served on the *Voyager* imaging team, and he was itching to go back to the outer planets.

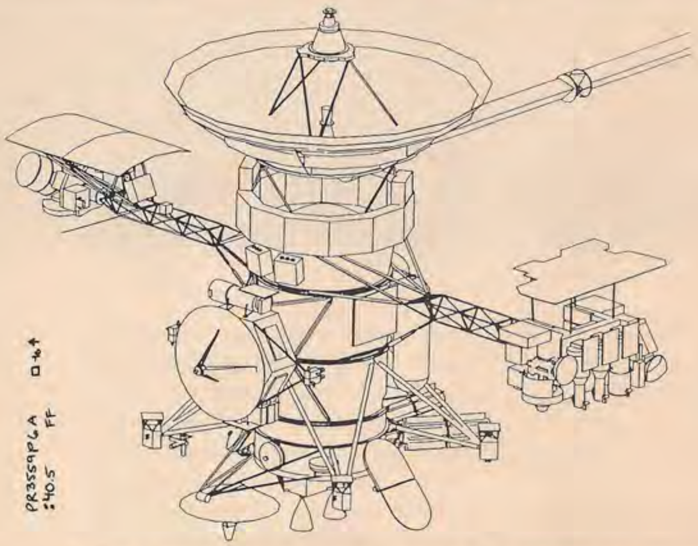
We set a stringent mass goal of 35 kilograms on the spacecraft; of that, 5 kilograms and 3 watts (out of 25 watts) were for science. Spacecraft engineer Hoppy Price came up with our first spacecraft configuration. The subsystems were "pasted" on the back of the antenna without a supporting bus—a radical mass-saving step. With Hoppy working on *Cassini*, we then recruited Chris Salvo to develop the spacecraft system design. We also brought in people from different disciplines, such as scheduling, accounting and public affairs, who normally would not have been involved this early in the game, and doing so proved invaluable in the long run.

We had a number of hurdles to jump: (1) Our peers were not used to seeing very small spacecraft and so tended to laugh at our attempt; (2) we had to garner, from OPSWG, the Solar System Exploration Subcommittee and the Committee on Planetary and Lunar Exploration, support for a quick trip to Pluto in which the much larger instrument payload that the groups had been considering for a first mission to Pluto would have to be greatly scaled back; and (3) we had to prove we could control costs. Luckily, senior JPL management and NASA headquarters were beginning to look for less expensive missions yielding more focused science results. So part of the money for the *MMII* Neptune/Pluto studies was parceled over to two Pluto mission developments: the "Pluto 350" mission (reborn from the 1990 design) and the "Pluto Fast Flyby," suggested by John Beckman, and so named because it could get to Pluto in less than half the time of the other designs; by this time, the orbiter concept had been dropped, having given birth to the fast flyby proposal. The Pluto arena was gearing up for a showdown between the two concepts. Life-cycle costs at first glance were a wash; the trade-off was between flight time and breadth of science. The debate went on through the April 1992 OPSWG midterm review. While NASA headquarters was leaning toward the fast flyby concept, no one could sign up to it without OPSWG endorsement.

Three weeks earlier, Dan Goldin had taken over as NASA administrator. His encouraging philosophies—to design better, faster, cheaper missions—coupled with the idea of empowering employees to make their own decisions (and be held accountable for the risk) were right in line with the Pluto Fast Flyby team's thinking. In May of 1992, Rob had the good fortune to be invited to attend a ceremony at the Motion Picture Academy of Arts and Sciences, at which Dan Goldin was to return Steven Spielberg's Oscar to the Academy after the statuette's sojourn aboard the space shuttle. When Rob told him that we wanted to launch in 1998, Goldin asked why we couldn't launch sooner. Rob handed him the team's half-inch-thick (double-sided) midterm report containing the mission details. Goldin promised to read it that night. He was soon asking Wes Huntress, then head of NASA's Solar System Exploration Division, how his Pluto mission was doing.

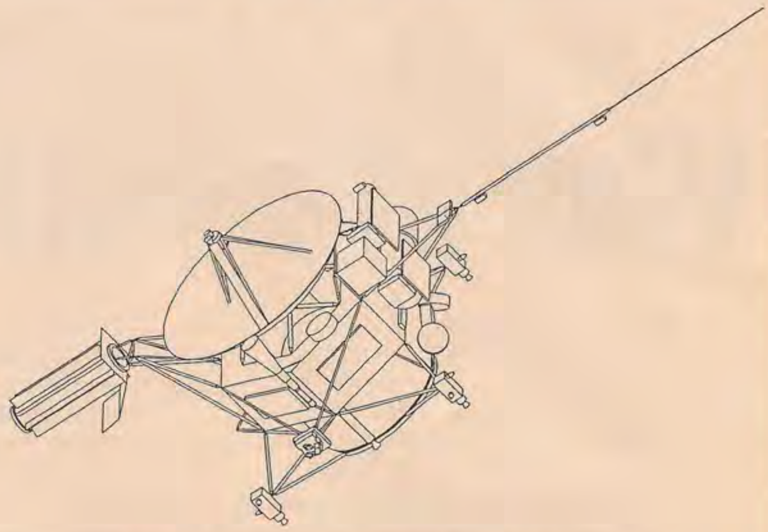
In the meantime, OPSWG chairman Alan Stern of the

Mariner Mark II Study



This early design for a Pluto mission was based on the Mariner Mark II *concept. Weighing over 2,000 kilograms (4,400 pounds), it would have taken 16 years to reach the planet and would have sent a daughter probe enabling it to see both sides of Pluto.*

Pluto 350 Design



This much smaller spacecraft would have weighed 350 kilograms (770 pounds) and could have been launched by the relatively small Delta 2 *rocket. It would have taken 13.6 years to reach Pluto.*

Southwest Research Institute and Rich had slowly begun to convince the other OPSWG members that there were small instruments that could be built to meet the Pluto mission's needs. After negotiations in July 1992, in which engineers and scientists worked side by side, a set of top-priority scientific objectives was established. Once OPSWG was satisfied that the Pluto Fast Flyby could accommodate these key objectives, the Pluto 350 concept was dropped, and the Pluto Fast Flyby mission development continued full steam ahead.

Why Pluto?

As the last first mission to a planet in our solar system, the Pluto mission holds phenomenal potential for discovery. If there is one lesson to be learned from the previous first planetary missions, it's that you can expect to be surprised. What little we already do know about this planet is fascinating.

With a diameter of about 2,300 kilometers (about 1,400 miles), Pluto is the smallest known planet. Its inclined and eccentric orbit around the Sun carries it between 30 and 50 times farther from the Sun than Earth is, and gives Pluto wide seasonal variations. Pluto has been observed over only a small portion of its 248-year orbit. It is the smallest, farthest, coldest, most difficult planet to explore; these properties make it the Mount Everest of planetary exploration.

Pluto has a thin atmosphere and a relatively large moon, Charon, orbiting at a distance of about 20,000 kilometers (12,400 miles). Methane is a constituent of Pluto's surface and its atmosphere; except for the recent spectroscopic detection of nitrogen and carbon monoxide, we know little about the other components. *Voyager* results suggest that Neptune's moon Triton is a near twin of Pluto in size and albedo (brightness). Triton has a complex geology, active surface eruptions, polar ice caps, seasonal surface frost changes and high-altitude hazes. As *Voyager* has demonstrated, only a spacecraft encounter can provide this kind of information.

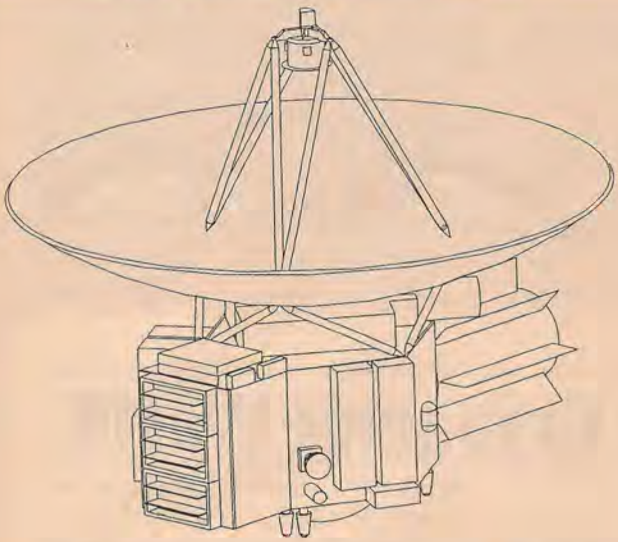
Pluto is now just past perihelion, its closest approach to the Sun. As it moves outward, it is cooling and its atmosphere is condensing. It is essential that Pluto be explored as soon as possible, from about 2005 to 2015, when its atmosphere is likely to freeze onto its surface for the next two centuries.

The onset of a deep southern-hemisphere winter is also plunging more and more of Pluto and Charon into long-term shadow, which would preclude mapping these regions. For about half of these bodies' 248-year orbit, their north polar regions point toward the Sun, leaving the opposite pole in shadow for decades. In 2005, less than 10 percent of Pluto will be in seasonal shadow. However, by 2015 the portion in shadow will increase to nearly 20 percent. By the 2030s, the polar orientation to the Sun will cause almost the maximum possible fraction of Pluto and Charon to be hidden in a decades-long shadow. This shadowing will not be significantly reversed until the 2060s. The last time humans had an opportunity to study Pluto near perihelion, a young George Washington was reportedly vandalizing cherry trees.

Challenging the Norms

"Studies need not apply," Rob was to admonish assembled industry representatives seeking Pluto-related contract opportunities at a November 1992 briefing. We asked aerospace engineers and marketers to tell us about real hardware they could build to help our little spacecraft lose even more weight. We were not interested in a lot of "what-if" analyses. We have each worked on a lot of studies, and they have their place for sifting through ideas by learning the merits, obstacles and feasibility of a variety of alternatives. But don't we already know enough to go to Pluto? Isn't visiting the last known, unexplored planet in our solar system a

Pluto Fast Flyby Spacecraft



By September 1993, this was the design of choice, weighing in at under 120 kilograms (about 260 pounds) with a mass "margin" left over for scientific instruments from international collaborators. This craft could reach its target in about eight years.

This full-sized mock-up of the Pluto Fast Flyby craft looks small, even with team members kneeling beside it. From left to right: Rich Terrile, Tom Rivellini and Rick Zitola.
Drawings and photograph: JPL/NASA. Drawings not to scale.

sufficiently compelling objective? Let's get on with it!

Well, it's never quite that simple.

By April of 1992 we had moved from our original fast flyby concept of a 35-kilogram probe carrying a camera and a radio to a slightly more robust, and realistic, 100-kilogram (220-pound) mass. We did not propose to actually fly this spacecraft, as without redundant subsystems it lacked the reliability needed for a seven-to-ten-year mission. Next, after a great deal of hard work by many experts at JPL and elsewhere contributing free overtime, we arrived at our so-called "1992 baseline" mission design. This 1992 baseline resulted after adding redundant subsystems and ensuring we could meet the OPSWG scientific objectives. The mass had grown to 164 kilograms (about 360 pounds), with a still comparatively swift flight time of about eight years. Working alongside our design engineers, students from the California Institute of Technology completed a full-size mock-up, and we shipped our first "hardware" August 21 to the World Space Congress in Washington, DC.

With the mock-up seen by thousands at NASA's exhibit, an end-to-end plan for how we would build, test, launch, operate and get the scientific results back from our mission, and a modestly detailed estimate showing that we could develop the mission for under $400 million, we proudly presented our results to OPSWG members and our NASA sponsors.

Having converted many critics along the way, we expected praise during the September close of the government's 1992 fiscal year. So we were shocked to learn that Dan Goldin, Wes Huntress' boss's boss, was furious. "What happened to 100 kilograms?" Goldin hadn't read the fine print—the part about reliability and more limited scientific objectives. "Don't let the bureaucrats spoil your beautiful dream!" Goldin said to Rob in his keynote speech at the World Space Congress.

"Go on a Diet!"

We were told to go on a diet, so we set ourselves a goal of 110 kilograms (about 240 pounds). Part of that diet involved curbing a voracious appetite for making every possible measurement at Pluto. Unfortunately, scientific instruments are usually expensive, massive and power hungry, requiring a larger, slower and more expensive spacecraft to support them. However, the data they gather are the reason to go to Pluto!

We have three primary goals set by the science community: (1) imaging the geology of Pluto and Charon, (2) mapping their surface composition and (3) characterizing Pluto's atmosphere. We are designing the spacecraft around just these primary goals. But, as it turns out, once you have instruments to meet these goals, you can also do much more. The challenge is to design these instruments so they fit into a small volume, consume very little power and are inexpensive. We are now confident of meeting our goal of 7 kilograms (15 pounds) and 6 watts.

When we started, the idea of having a payload weighing less than 10 kilograms (22 pounds) was met with some skepticism and resistance. Now, after studying miniature instruments that have already been built, and having scientists around the country build working prototypes of key components, we believe we can satisfy the scientific community's three goals with a very small and affordable instrument package that can return more data from Pluto than *Voyager* did from Triton.

It's one thing to be told to lose weight; it's another to be given the proper resources to attack the problem! With the Advanced Technology Insertion (ATI) process, we were given $5 million for two years to shop for lightweight components and subsystems using new technology never tried on a planetary mission. First, we surveyed industry, federal labs and academia for Pluto-applicable hardware. This survey provided the information needed to solicit focused "Requests for Proposals" (RFPs). Successful bidders are now building, and many have delivered, critical items such as an antenna, electronics, operations software and propulsion components that are lighter, smaller, quicker, and/or use less power than any ever flown on a planetary mission. These are to serve as proofs-of-concept. While not flight qualified, these components cost a fraction of the cost of flight hardware and give us time to learn what will work and what won't for our unique mission. In many cases, our ATI funding is insufficient to cover each proposed design and proof-of-concept effort, so participants are augmenting their Pluto money with internal corporate and university research accounts to achieve their goals. ATI results are not paper studies, but actual products we test.

Hot Science on a Cryogenic World

by Alan Stern

As a scientist, I usually feel like a high-tech detective, trying to unravel mysteries even Agatha Christie would cringe at. However, with Pluto, I and many of my colleagues feel like kids at Hanukkah (or Christmas), trying to unwrap presents our siblings hardly imagined could ever (really) be for us. It's as if the best was saved for last.

In the last decade, there has been an incredible explosion of knowledge about the little binary planet Pluto–Charon, which is poised on the ragged edge of the planetary system. Imagine, since 1978 we have learned that Pluto is smaller than ever expected, but also rockier. That Pluto's orbit is chaotic over astronomical timescales. That Pluto is covered with exotic, super-volatile snows of nitrogen (N_2), methane (CH_4) and carbon monoxide (CO), but its sole satellite, Charon, is encased in run-of-the-mill water ices. That Pluto's surface seems to be unusually diverse, with polar caps, hot spots, and markings as distinct as any on the inner planets. That Pluto's puffy, distended atmosphere is escaping from it so fast that surface features can "escape away" over geologic time. That Pluto is the only true double planet in the solar system (Charon is exactly half Pluto's diameter). That some of Pluto's tenuous upper atmosphere probably spills over into orbit about Charon, as if it were a tightly orbiting binary star. That Pluto's atmosphere comes and goes with each orbit, like some giant, planetary-scale comet with four seasons that make any others in the solar system, save Triton's, look wan and wimpy by comparison. And that Pluto is very likely a leftover mini-planet, the largest of the 1,000-plus ice dwarf mini-planets, which seem now to make up the most populous class of planetary bodies our solar system has produced. Through the mists that hindsight clears, we are now coming to appreciate that Pluto, the world we left till last, may be more complex than Io, Triton and even Mars. Time, sweat-equity and the eye-opening explorations of *Voyager* have revealed that Pluto is a relic, and a reporter, and a renegade from the era of formation of Neptune, Uranus and the Kuiper comet disk. And now we are capable of reaching it.

I saw the Moon become a real place in my childhood, followed by Mars in my adolescence. Jupiter, Saturn, and the wild ones, Uranus and Neptune, became places when I was in college and graduate school. And yet to me, like many other younger planetary scientists, all these seem rather like My Father's Oldsmobile. Pluto is ours! It's the little planet that could, the measure of our imagination and resolve, the top of the pyramid, the Everest for our planetary generation.

Pluto (or, more properly, Pluto–Charon) is also the last "astronomer's planet." It is the one on which we will finally know if the hard-won lessons of the *Rangers*, the *Mariners*, the *Vikings* and the *Voyagers* were sufficient. It is the world on which we will learn whether we can, after all our early explorations, get a planet right from our telescopes and space-based observatories. It is the world on which we will learn whether we have gained a sufficiently deep and diverse background to imagine (in any real sense) the diverse worlds of other solar systems that we will soon plumb by telescope.

What amazes me about Pluto–Charon is that it is a mirror. Some look, and see it as the frontier of exploration. Others see a unique double planet. Some see an analogue to Titan and Triton, while others see the largest ice dwarf of the Kuiper disk. Some see the chance to study the physics of hydrodynamically escaping atmospheres (read: comets on a planetary scale), but others see the best analogy to the Earth–Moon system and the ancient, giant impact that created our Terra and Luna. Each sees something different, but they are all correct.

Long ago it was written: There is a time for every season under heaven. Let us extend our grasp, explore this strange new binary world and see if our children can discover, as we did ourselves, what Nature can do with a few ices and minerals, a little classical low-temperature physics, and a time span a thousand times our own.

Alan Stern is a planetary scientist at Southwest Research Institute in Boulder, Colorado.

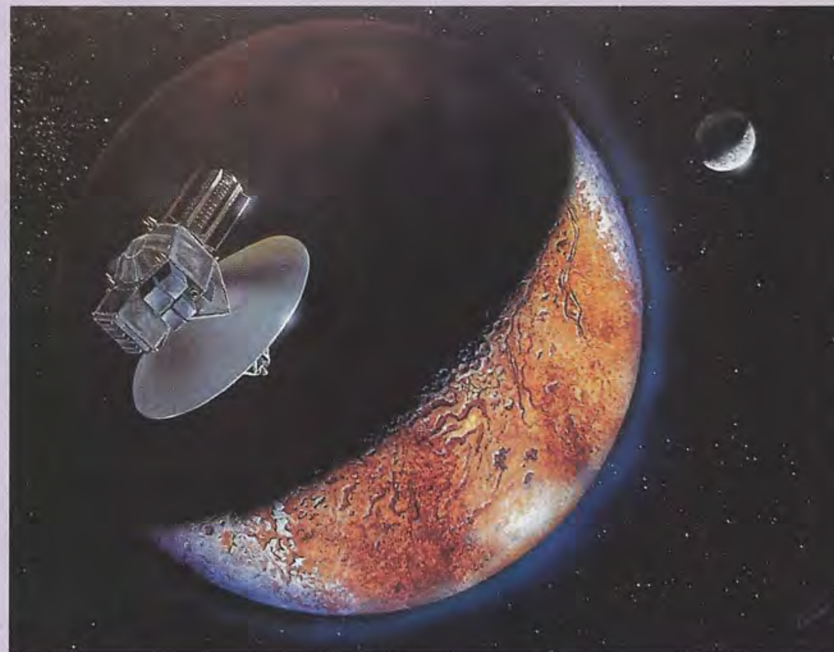
We set aside a small portion of ATI money for student-led projects. The same rules apply: The products must be tangible, not paper studies. A number of university proposals were considered and several funded; one has even shown commercial "spin-off" potential for personal telecommunications. We are committed to involving students in mission development and, later, in mission operations.

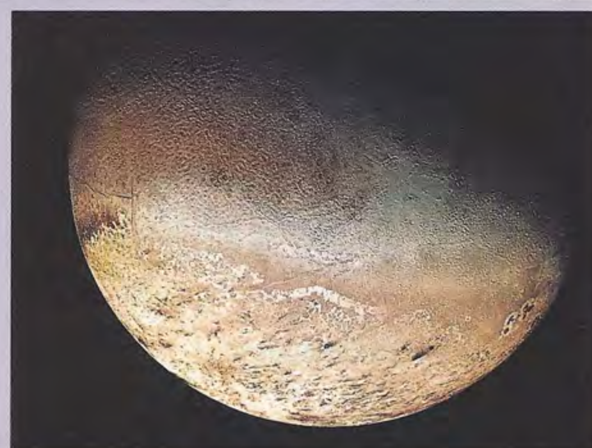
Taking Risks

Our design in September, at the end of fiscal 1992, was indeed conservative, as Goldin had noted. With a lot of innovation from people at JPL, in industry, at universities and other government laboratories, we got our September 1993 mass down under 120 kilograms (about 260 pounds). We have added some mass back since then, with an enlarged antenna and power source; these changes brought life-cycle cost savings of tens of millions of dollars, making the slight mass increase worthwhile. A generous mass "margin," or reserve, remains, which may be used for a science payload from international collaborators, perhaps space physics instrumentation, or other inexpensive additions.

There is a lot of newer technology in our lighter design. And "newer" typically means "unproved," implying greater risk. This seems to be exactly what Dan Goldin is imploring us, and funding us, to do. Many within our industry feel that much of the industry has become too risk-averse, and perhaps too comfortable with minor upgrades of yesterday's technology. The US didn't put people on the Moon with "comfortable" or risk-averse technology. Nor did the Soviets and Americans launch the first planetary probes in this manner. If the US and NASA are not going to put the vanguard of technology into the first mission to Pluto, where are we going to put it? What will we use to lead ourselves into the next millennium?

So if our entire science activity can be accomplished with instruments that together weigh a fraction of today's spaceborne interplanetary television cameras, and if all the data we collect at Pluto are stored in a computer memory weighing less than many of today's computer keyboards, and if our high-gain antenna to send signals about 4 light-hours back to Earth weighs about the same as the telephones on our desks, perhaps we will have helped push technological achievement. And perhaps we will plant the seeds for the next generation of robotic space exploration, whose designers of 7-kilogram Mars rovers and 25-kilogram (55-pound) asteroid explorers will wonder why we did not consider 100-plus kilograms to be the height of extravagance. Indeed, such plans are on the horizon, and we must work knowing that if we are successful our achievement will soon be eclipsed.





Top: The Pluto Fast Flyby spacecraft approaches the planet and its large moon, Charon. This is the only true double planet in our solar system, with the moon having half the diameter of the planet. By comparison, Earth's relatively large Moon is just over one-quarter of the planet's diameter. Pluto's atmosphere is also unique, coming and going with each orbit as the planet approaches, then retreats from the Sun. These and many other features tantalize scientists with the prospect of completing our reconnaissance of the solar system. Painting: Michael Carroll

Bottom: Some scientists have suggested that Neptune's moon Triton, visited by Voyager 2 ***in 1989, may be a close relative of Pluto and that their icy faces may be very similar. Others feel that, based on what few features we can make out from Earth, they are very different worlds. Whatever the case, we won't know until we fly there—perhaps before the next decade is out.*** Image: JPL/NASA

The Next Steps

Our success with this initial design and proof-of-concept phase has brought us "breadboard" hardware and software in 1994. By this we mean our team members have created critical portions of the spacecraft and ground equipment in effect on a small number of workbenches in laboratories.

The first mission equipment we build, following that built in our current ATI phase, often won't look much like a spacecraft, but it will demonstrate that we can perform the necessary functions at the level of components (like a radio receiver) and subsystems (such as propulsion). Testing is in progress to verify critical electronic and mechanical functions of sensors, thrusters, valves, computers, electronic memory and so on. Computer software, some of it written on ordinary personal computers, has begun to verify our scheme to send commands to the spacecraft, and to govern interactions between different parts of the spacecraft and ground equipment. This early software will be used and upgraded to test as we build, and will evolve into the computer commands to be loaded on board the spacecraft.

Our next step, planned to start in 1995, is "brassboard" equipment. This hardware and software will be close in form, fit and function to what we plan to fly, but it will lack the reliability and thoroughness needed for the actual mission. The breadboard-level testing is expected to reveal flaws in our design and show better ways we can implement complex functions, such as routing data from the camera to the memory. These lessons will be incorporated into the brassboard equipment, which will look similar to what we plan to fly, but will generally be heavier. Because breadboard hardware is the least expensive, and brassboard equipment much less expensive than flight equipment, problems found and solved at these stages are much easier to fix than those uncovered after we have a larger team working with expensive, flight-quality parts.

If we avoid many pitfalls, inspire enough supporters and garner the needed political support to proceed, we are hopeful of a "new start" in fiscal 1996, where the Pluto mission or its key technologies would be funded as an individual line item in the federal budget. (Funding up to this stage comes from advanced-development budgets.)

There is a great deal of competition among worthy projects of all kinds for limited funds. However, we believe that we owe the nation something more than the images and knowledge of the last planet. Many of us on the Pluto team grew up during the high visibility of the *Apollo*-era space program, a time when the nation put great value on the role NASA played in feeding high technology into the private sector. This perception inspired many young people to pursue careers in the sciences and is directly responsible for our participation in the Pluto mission. Now we would like to return the favor by giving some of the old NASA excitement back to the nation. We do this by mandating that the newest technologies be used, by challenging ourselves to build small, (relatively) inexpensive but sophisticated spacecraft, and by reaching out to communicate our pursuit to the young.

When we do begin building our flight equipment, the progressive design–build–test cycles of the ATI, breadboard and brassboard phases are expected to have driven out nearly all of the major kinds of problems we are expecting. Of course, it is the problems we are not anticipating that most worry us, so building the flight equipment will be no piece of cake. But we are carrying healthy cost and schedule reserves to deal with the unexpected problems we all know will be there.

The Planetary Society Advances

by Louis D. Friedman

The idea of a fast flyby mission to Pluto has generated a lot of excitement. A lightweight spacecraft using advanced miniaturized technology could offer a relatively quick and inexpensive way to complete the initial reconnaissance of the solar system.

But even by reducing the estimated cost with innovative spacecraft and mission design, the mission still requires a large and powerful rocket to launch it to the outskirts of the solar system. The only rocket in the United States' stable big enough would be the *Titan 4*, which would cost nearly $500 million.

In conversations with Planetary Society officers, NASA Administrator Dan Goldin expressed great interest in the Pluto proposal but tempered his enthusiasm with concern that the cost of the mission would prevent it from ever being done. Although Goldin felt that the Jet Propulsion Laboratory's efforts to come up with a lighter spacecraft and a faster mission were truly innovative, the cost was still too great.

We began thinking about a joint mission with the Russians. They have a rocket powerful enough to send a spacecraft to Pluto: the *Proton*. And they could provide the launch for a much lower cost than the US could. In a cooperative program, JPL could focus on the high technology needed to build a very lightweight spacecraft. Experienced scientists, engineers and managers in both countries could contribute to mission design and to the science instruments.

But at the time we floated this proposal, in mid 1993, NASA was not permitted to consider joint missions or *Proton* launches. Well, we thought, maybe NASA couldn't consider such things—but The Planetary Society could. Furthermore, as a free entity funded by our members and not by governments, we could ignore the bureaucratic restrictions. We could go straight to the source: the Russian space organizations responsible for planetary missions, spacecraft and launch vehicles.

Within a few weeks we forged an agreement with the Russian space organizations and drafted a contract with the Space Research Institute of the Russian Academy of Sciences to head the study. The other organizations involved were NPO Lavochkin (spacecraft and mission design), Khrunichev (the *Proton* manufacturer), Moscow Aviation Institute (ion thrusters), NPO Energia (ion thrusters and other propulsion options) and Soyuz (upper-stage propulsion modules).

On the US side, we engaged former JPL Associate Director Harris ("Bud") Schurmeier, one of the world's most experienced planetary project managers, to organize a US review team to work with the Russians in analyzing important technical issues. Then we told NASA we'd complete the study in just a few months and give the results to them.

That's just what we did.

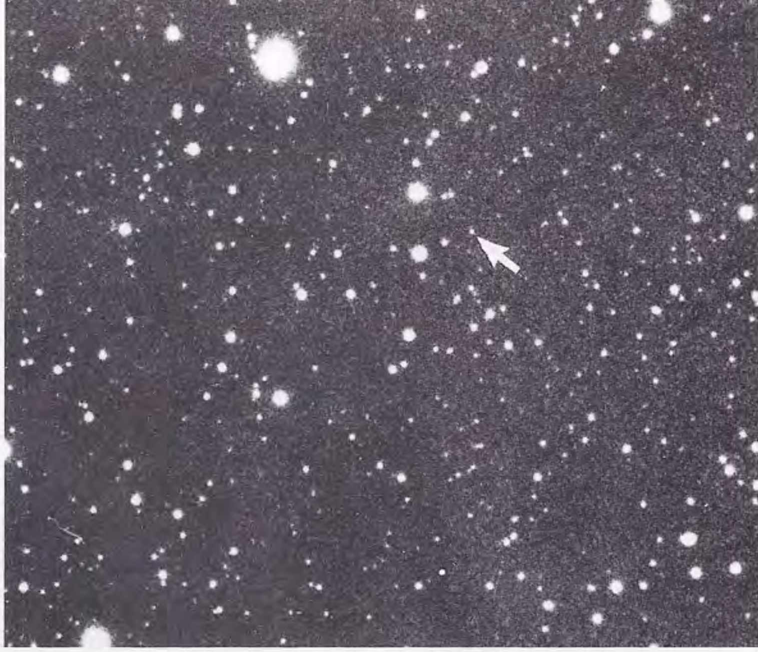
On February 14—Valentine's Day—1994, the Russian

If we are not forthcoming with every cost-saving innovation in both what we do and the way in which we do it, there will in all probability be no mission. If at any time it appears that we cannot meet our objectives within the budget agreed upon with NASA, we can expect our project to be canceled.

In today's climate, we cannot afford to be slow. Time is money. And the willingness of taxpayers to support this mission of exploration and inspiration is a privilege that can be revoked at any time. Add to this the standard of excellence for planetary missions that have preceded us, and we have a very big challenge ahead.

We can use all the encouragement we can get, and we appreciate your support.

Rob Staehle is manager of the Pluto Fast Flyby Preproject at the Jet Propulsion Laboratory. Rich Terrile, Pluto Preproject scientist, is an astronomer in JPL's Earth Space Science Division. Stacy Weinstein, Pluto mission design and launch vehicle lead engineer, is in the Advanced Projects Group of JPL's Mission Design Section. Work described here was supported by NASA's Office of Advanced Concepts and Technology, the Office of Space Science, other government agencies, universities and private companies.



How did Pluto evade planetary watchers until 1930? This discovery photograph gives some idea of the problem. The tiny speck indicated by the arrow is what Clyde Tombaugh picked out as a moving object against the background of fixed stars. **Photograph: Lowell Observatory**

Cooperation in Pluto Exploration

study team leaders presented their recommendations to a delegation from the JPL Pluto team. The Russians came up with several options for launching the Pluto spacecraft on a *Proton.* They also offered different upper-stage concepts for taking the spacecraft from near-Earth space to an interplanetary trajectory. They explored the use of electric propulsion for an upper stage, based on the considerable flight experience they have had with ion thrusters.

The Space Research Institute group made an intriguing, and unexpected, suggestion—namely, to launch an ultralight probe from the Pluto spacecraft into the planet's atmosphere. This Russian contribution would lift the Pluto mission from the flyby class by adding the direct measurement of the planet's atmosphere.

Bud Schurmeier's team reviewed the Russian results and recommended some follow-up questions and studies. NASA and JPL were very positive about the study. We sent a report to NASA Associate Administrator Wes Huntress, who applauded the Society's initiative and the Russian study team's work. He also indicated that NASA was going to begin a joint American–Russian study of the mission.

In fact, Huntress came up with an innovative proposal of his own: combine the Pluto Fast Flyby mission and the proposed Solar Probe into a single project, to be called Fire and Ice. In this project, two former adversaries could join in exploring the ends of the solar system.

Both the Solar Probe and the Pluto mission have about the same launch requirements, and both will go out to Jupiter, where the Solar Probe would use a gravitational assist to fly back directly to the Sun. Thus much, although obviously not all, of the spacecraft requirements could be met by coordinating the design of the two missions.

At the Society, we are excited by the positive response from NASA and the bold leadership of Wes Huntress. Fire and Ice is now an official US–Russian study undertaken by a team working on new joint mission concepts. It's a far cry from past years, when NASA resisted outside interest and NASA managers did not seek out new ideas—especially international ones.

In a letter to the Society, Huntress applauded the strong support from our members, who made this Pluto study possible. "I believe that the interest demonstrated by your membership in such a bold venture is shared by the majority of the American public," he wrote. We believe that too, and if we work with the Russians to lower costs and pool expertise, an exciting program like Fire and Ice could be popular enough to succeed.

Louis D. Friedman is Executive Director of The Planetary Society. He coauthored the first technical paper proposing the Solar Probe mission in 1974.

Sifting Through the Data:

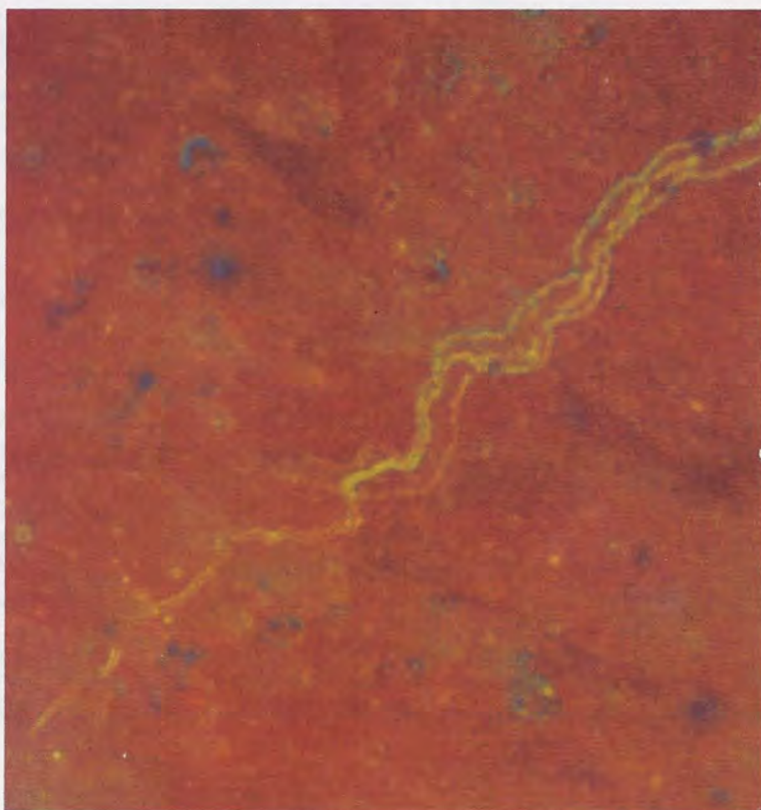
This is a close-up of Aristarchus crater, which is 42 kilometers (26 miles) wide. (The mosaic on our cover shows the surrounding area.)

The bright spots in the center of the crater represent its central peak, composed of almost pure anorthosite, a primitive rock type produced by the magma ocean that once covered the Moon. The anorthosite may be common in this area, buried beneath lavas from later molten seas and material ejected by the impact that formed the great Imbrium basin.

She's not lost and gone forever, but *Clementine,* the small spacecraft sent to the Moon by the Ballistic Missile Defense Organization, has encountered a bit of trouble after successfully completing her mission to map the lunar surface. She was launched on January 25, 1994, reached lunar orbit on February 19, mapped the Moon, and left orbit on May 3. *Clementine* was then sent on her way to investigate the asteroid Geographos. But on May 7 her housekeeping computer malfunctioned, leading to the depletion of the attitude-control propellant and condemning the asteroid mission.

The little spacecraft has been turned back toward Earth. She has entered an orbit that will take her repeatedly through the Van Allen radiation belts. That extreme radiation environment will stress her sensors and test the durability of her new technology systems. The asteroid mission has been lost, but *Clementine* will continue to return data that will be useful to spacecraft developers.

Meanwhile, scientists on Earth are mining the rich store of data from her successful lunar mission. *Clemen-*



The Aristarchus plateau, rising 3 kilometers (2 miles) above the surrounding lava plains, has the densest concentration of lunar sinuous rilles (snake-like valleys formed by fast-moving molten lava) of any area on the Moon. The largest rille, shown here, is Vallis Schroteri, about 160 kilometers (100 miles) long, up to 11 kilometers (about 7 miles) wide and 1 kilometer (0.6 mile) deep. (This rille is also visible on our cover.) The rilles in this area originated from "cobra-head" craters that appear to be vents for the thin lavas that formed them.

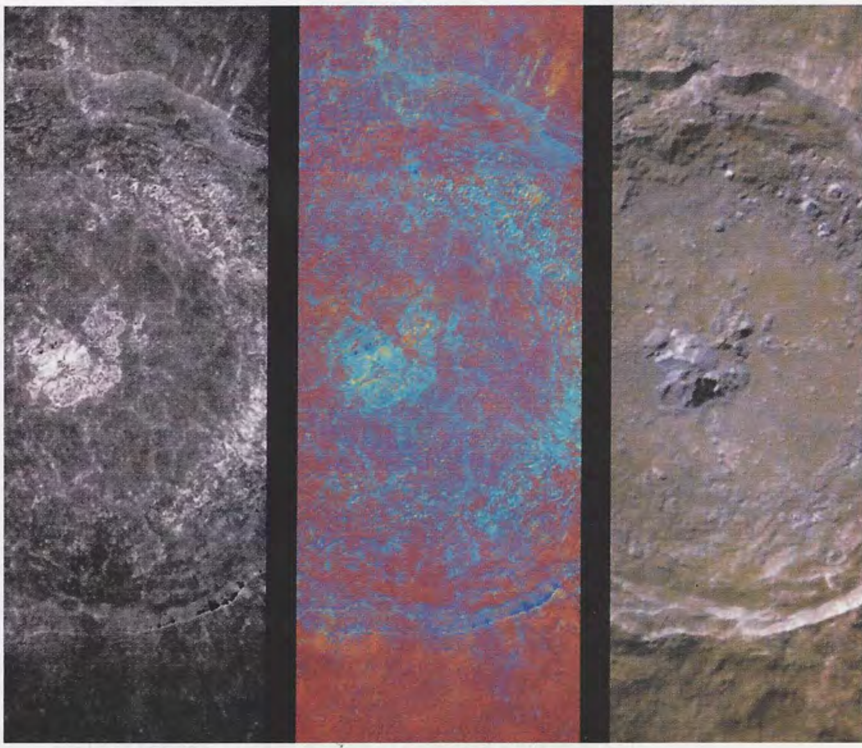
These cobra-heads, and other volcanic craters, may have been the vents for a "dark mantling" deposit (shown in this false-color mosaic as dark red) covering the nearby areas to the north and east.

Clementine's Lunar Bonanza

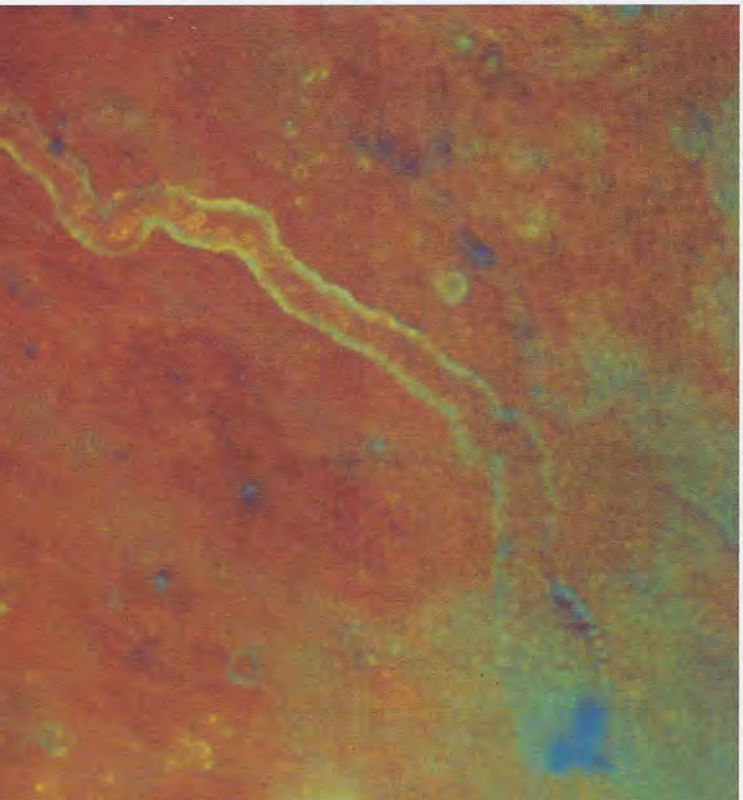
tine was the first spacecraft to map the Moon's surface completely. On these two pages, and on our cover, we present just a few of the images she returned. Because *Clementine*'s instruments were equipped with different colored filters, she was able to collect different colors of light reflected from the lunar surface. The information contained in these multispectral images will allow scientists to identify minerals in the rocks, giving us the first compositional map of the entire Moon. (See the September/October 1993 issue of *The Planetary Report*.)

Clementine also carried a laser ranging system. Its measurements have given us a very detailed picture of the lunar topography, and the data are being used to refine maps of the Moon's surface.

There will be years of work to do before the data return is panned out. Over the next few months, we may be hearing of surprising discoveries from *Clementine*, but some of the most valuable return may come from *Clementine*'s tangible proof that small spacecraft can uncover rich lodes of data. —*Charlene M. Anderson*



Here are three mosaics of the same scene over the crater Tycho, which is 85 kilometers (53 miles) in diameter. At right is a "stretched" color mosaic of the crater, exaggerating the relatively blue color of the central peak. The central peak is derived from deep below the crater floor and thus represents the rock types found deep within the Moon. The false-color version (center) further exaggerates these color contrasts and allows different rock units to be distinguished. Here reds represent calcium- and aluminum-rich feldspar (anorthositic rocks), while blues correspond to rocks containing pyroxene, an iron- and magnesium-rich silicate mineral. The monochrome ratio image (left) shows the location of fresh, mafic material, minerals relatively rich in iron and magnesium, which are bright in this image.



***Clementine*'s Star-tracker camera caught this picture of Venus over the Moon. Although the Sun is tucked away out of sight, its bright corona glows beyond the lunar limb. Part of the Moon's surface is illuminated by light reflected from home—Earthshine.**

Images: Naval Research Laboratory/Processing: United States Geological Survey, Flagstaff

TWO FOR THE ROAD: NEW HOPE

BY LOUIS D. FRIEDMAN

Mars Together, and Fire and Ice, two exciting studies for solar system missions, have just been endorsed by United States Vice President Al Gore and Russian Prime Minister Viktor Chernomyrdin. Both studies grew out of Planetary Society proposals.

In Mars Together, the two nations would pool resources and merge national plans to explore the Red Planet. The other proposal, Fire and Ice, to investigate Pluto and the Sun, grew out of a Pluto mission study paid for by Planetary Society members (see page 10).

The Mars proposal would send two spacecraft to Mars at every biennial opportunity, beginning in 1998. What makes this proposal unique is that one spacecraft would be launched on a US vehicle; the other, on a Russian *Proton*. Each launch would carry equipment and experiments developed in both nations. The program is being coordinated with the International Mars Exploration Working Group, the European Space Agency, France, Germany, Italy and Japan.

The idea for a Russian/US launch strategy and the pooling of resources was developed at a Society workshop held last February. We presented the workshop's recommendations to the world's space agencies in a document entitled "Exploring Mars Into the 21st Century." The plan is ambitious, with numerous exploratory vehicles launched to Mars over eight years. The international scope is unprecedented.

Now NASA and the Russian Space Agency (RKA) have been ordered to further develop the Mars and Pluto proposals. According to the official report, Vice President Gore and Prime Minister Chernomyrdin "directed the scientists on both sides to complete the initial studies and report their findings" at the next meeting of the US–Russian Joint Commission on Economic and Technological Cooperation, which will be held in December. Excerpts from the plan they officially endorsed are reprinted below.

We can all take a great deal of parental pride in this endorsement at the highest levels in both governments. But we should keep in mind these caveats: All of the missions will be extremely cost-constrained. The US Mars Surveyor program has very ambitious technology and cost goals. Russia has recently postponed two long-planned Mars missions, *Mars '94* and *'96*. And budgets in both countries are limited.

Still, the fact that Earth's spacefaring nations are now agreeing to work together to share costs and enhance potential discoveries is a cause for celebration. We can all feel hopeful that there is going to be a real renewal in planetary exploration.

Louis D. Friedman was formerly manager of the Mars program at the Jet Propulsion Laboratory.

PLAN FOR U.S.-RUSSIAN COOPERATION IN SPACE SCIENCE

The following excerpts are taken from the text of the plan prepared for the Gore-Chernomyrdin Commission on Energy and Space by NASA, the Russian Space Agency and the Russian Academy of Sciences in June 1994.

"FIRE AND ICE"

Both sides agreed to study a concept in which the U.S. and Russia would explore together the extreme ends of the solar system: the Sun ("FIRE") at the center and Pluto ("ICE") at the outer boundary.

SOLAR PROBE: The proposed study incorporates an American solar probe spacecraft carrying a Russian instrument payload or module which would fly by the Sun at a very close distance. . . . The U.S. could develop a miniaturized scientific payload to study the in-situ plasma and particle environments, while Russia could develop an instrument module that can observe, remotely, more global phenomena. . . . The U.S. could capitalize on its extensive design history . . . while Russia could contribute the high-performance and reliable launch vehicle (Proton), as well as the instrument module.

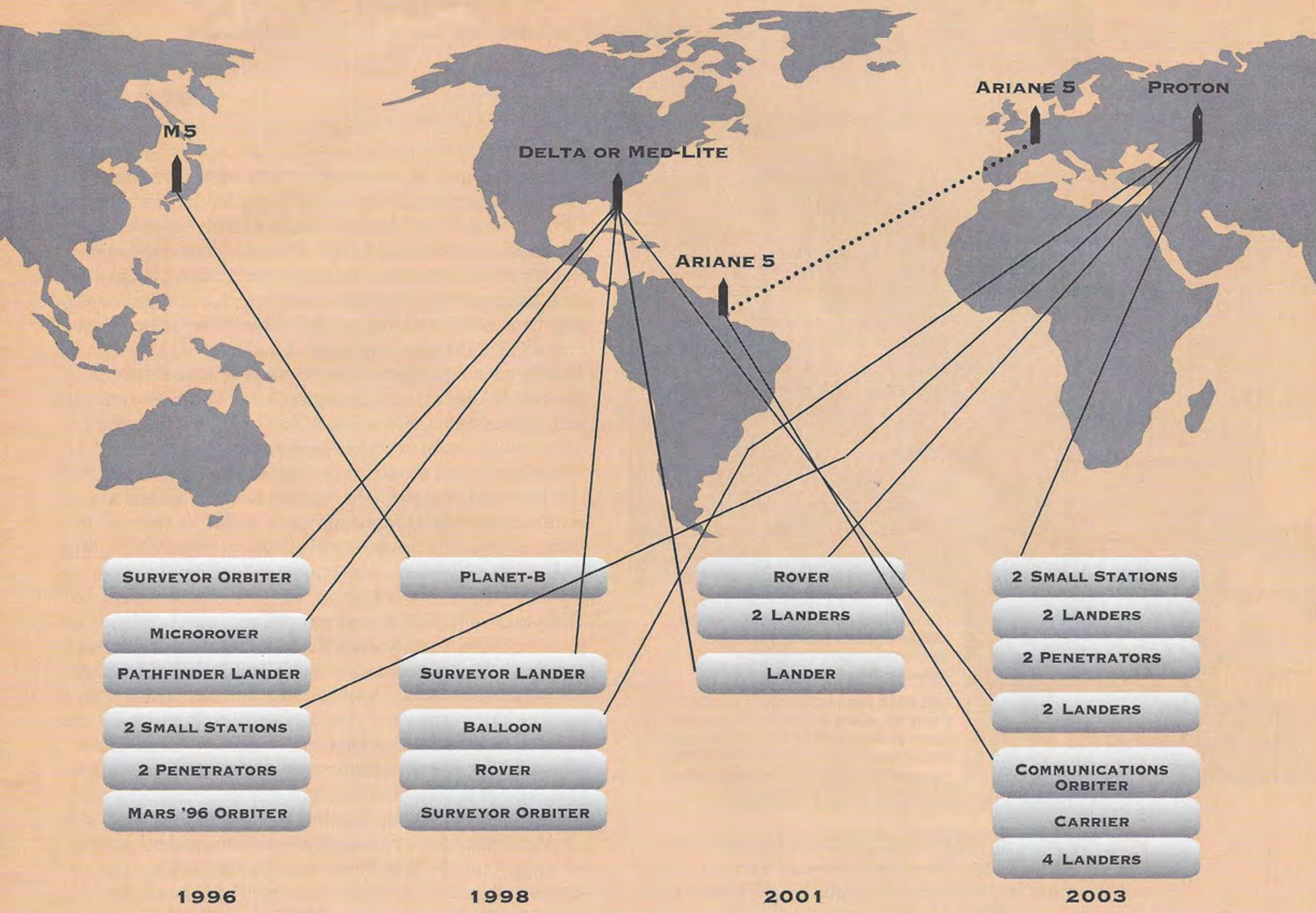
PLUTO FLYBY: Because of the large distance to Pluto, a combination of lightweight spacecraft and high-performance launch vehicle is required to reach Pluto in a reasonable time (less than 10 years). . . . The concept is to use a U.S. miniaturized spacecraft with new instrument technology, together with Russian launch vehicle capability and a Russian-developed drop-sonde [probe] for in-situ atmospheric measurement and [possibly] surface high-resolution imaging. The U.S. flyby spacecraft would transport the Russian surface probes to Pluto/Charon and relay their data to Earth.

MARS EXPLORATION

The sides agreed that since both the U.S. and Russia have a strong, continuing interest in Mars exploration, with each intending to fly independently several missions to Mars in the next decade, it would be mutually beneficial to study options to initiate a new level of cooperation in the planning and implementation of Mars exploration activities. Cooperation would strengthen both programs scientifically, technically, and programmatically, would provide increased levels of program and technical resilience through exchanges of launch and instrument flight opportunities, and would facilitate the transition to a completely international Mars exploration program.

It is envisioned that a cooperative Mars exploration program could consist of two launches, one U.S. and one Russian, at each opportunity, with the payloads consisting of both U.S. and Russian spacecraft and instruments, and would focus on the 1998 and 2001 launch opportunities. □

FOR EXPLORATION IN SPACE



The ambition and the international character of the Mars Together plan are easy to see in this chart. Along the bottom axis are the dates of launch. The various spacecraft planned for launch at each approximately two-year Mars opportunity are listed above. The lines extend to the countries responsible for launching those craft to Mars. This is a sample scenario that is under study. Variations, especially for the 2001 and 2003 plans, are also under study.

THESE ARE THE SPACECRAFT THAT WOULD BE SENT TO MARS:

- *Surveyor Orbiter: US polar orbiter that will make geological and climatological observations. The first two, to be launched in 1996 and 1998, would carry duplicates of the instruments lost with Mars Observer.*
- *Pathfinder: A small US lander to launch in 1996.*
- *Microrover: A 6-kilogram mobile explorer to be deployed from the Pathfinder lander.*
- *Mars '96 Orbiter: Postponed from its 1994 launch, this is a large spacecraft to take remote sensing measurements of the planet.*
- *Small Station: A small Russian lander that will study the martian surface. It will be deployed from the Mars '96 orbiter and will land on air bags, without using a retro-propulsion system. It will also carry the names of all Planetary Society members as of October 1993.*
- *Penetrator: An instrument-laden device, shaped like a small missile, that will be deployed from the Mars '96 orbiter. It will land point first, penetrating below the surface.*
- *Planet-B: A Japanese orbiter that will study the upper atmosphere of Mars.*
- *Lander: A small, high-technology spacecraft, built in the emerging Mars Surveyor program.*
- *Mars Balloon: A French-built balloon, carrying instruments and a Planetary Society–designed guide-rope, that will investigate the planet's surface and winds.*
- *Mars Rover: A mobile robot that will carry instruments across the surface.*
- *Communications Orbiter: A spacecraft that will serve as a communications relay between Earth and landers on Mars. The Italian space agency has expressed interest in building this orbiter.*
- *Carrier: A spacecraft bus that carries Mars landing vehicles.*

Chart: Louis D. Friedman; drawn by B. S. Smith

Advancing Our Ambitions: The 1994 Mars Rover Tests

by Charlene M. Anderson

Above: The rover's familiar appearance changed for parts of these tests with the addition of a manipulator arm built by McDonnell Douglas Aerospace.
Photograph: James D. Burke

Left: NASA Administrator Daniel Goldin (pointing), sitting in our remote command center in Anaheim, took the rover for an extended run across the lava fields of Amboy.
Photograph: Wade Sisler, NASA Ames Research Center

Sometimes at The Planetary Society, our ambitions exceed our reach. But that's the way we want it, for it means that we are always pushing the boundaries of what we and planetary explorers can do.

This spring, we held our most ambitious tests yet of the Mars Rover. We built a team of Russian and American scientists and engineers from government space agencies, universities and industry. We sent the rover to test its mettle in a lava field in the Mojave Desert. We set up remote command centers, devised tests of telepresence and virtual reality—and then, we invited the public to join us.

What were the results? Well, we learned that the needs of scientists, engineers and the public sometimes conflict. And we learned that the 10-day period we had was not long enough to do all we wanted to do. But we made great progress in implementing the new telerobotics technologies for planetary exploration.

A Little History

When we first became involved in working with the Russians on the Mars Rover, in 1989, tests focused on engineering—on the six-wheeled robot's ability to traverse dangerous terrain. Our 1992 tests in Death Valley involved the Society in testing navigation algorithms that would provide the rover with some degree of autonomy in its travels across Mars. (See the November/December 1992 and January/February 1993 issues of *The Planetary Report*.) This "obstacle-avoidance" software ran on an onboard computer. Various sensors on the rover kept the computer informed about such things as the tilt of the wheels, which might indicate that the rover was scaling an obstacle too steep to be safe.

In 1993, a group of engineers at McDonnell Douglas Aerospace and members of the innovative telerobotics group at NASA's Ames Research Center began to work with us and with the Russians. Our goal was to use the developing computer technologies of telepresence and virtual reality to enhance the remote control of the rover. Our tests that year, with the rover in Kamchatka and a control center in California, proved the idea had merit. (See the January/February 1994 *Planetary Report*.)

Spring Tests, 1994

This year, we tackled science operations. Ron Greeley, a planetary scientist at Arizona State University, put together a test plan. He worked closely with Carol Stoker of NASA's Ames Research Center, who has been a leader in applying telepresence to lunar and planetary surface operations. They recruited scientists for a working group whose prime objective was to determine how to use the rover's mobility to maximize the scientific return.

The scientists split up into four teams.The first two simulated operations with the rover on Mars and operators on Earth. One, the Blue Team, was familiar with the test site; the other, the Red Team, was not. The Green Team worked with the rover in the field and provided the equivalent of "ground truth." The fourth, the Lunar Team, simulated operations on the Moon.

The biggest difference between remotely operating a rover on the Moon and operating one on Mars will be the time it takes radio signals to travel from Earth to the rover and back again. For the Moon, the one-way time is less than 1 ½ seconds; for Mars, it ranges from 8 to 20 minutes, depending on the distance between Earth and Mars at the time.

This means that there can be a much quicker flow of data between a rover on the Moon and an operator on Earth than will be possible in martian operations. So, a lunar rover could send back live stereo video to help its navigator drive it across the surface, while a martian rover will probably be limited to sending pairs of still stereo images every few minutes. The navigator will have to build up knowledge of the surrounding martian terrain laboriously, image by image.

Our Lunar Team had the luxury of live video and high-resolution stereoscopic color cameras, while the two Mars teams were limited to the lower-quality black-and-white

Is it a 1950s movie audience watching a 3-D horror film? No, it's just a group of attendees at the National Science Teachers Association convention watching a stereo video of the rover traversing the desert terrain at Amboy Crater. Photograph: Wade Sisler, NASA Ames Research Center

Even tracks in the sand yielded data for the science teams. At this site they were measuring the digging potential of one pair of the rover's six wheels. Photograph: Wade Sisler, NASA Ames Research Center

stereo pairs. Both the Mars teams and the Lunar Team worked with simulated descent images (taken with cameras in airplanes and helicopters), similar to those that might be taken as the spacecraft moved toward its landing site. Images from Landsat and Spot simulated orbiter images.

The test site was the lava field surrounding the Amboy volcanic crater in the Mojave Desert. The relatively young basaltic lava flows have much of their original texture, although windblown sand and dust have covered some of the lava. The Amboy lava field is similar to many areas of Mars that are of high priority for future lander and rover missions.

Science Results

The Mars science teams had four objectives. Using rover images, they were to (1) locate the landing site by identifying features seen in the descent images, (2) analyze soil at the site, (3) search for and identify rocks and (4) find and examine a rock outcrop in cross section. They completed all tests but the last. They simply ran out of time.

While the rover was mainly used to seek out and enable the team to identify rocks, it did perform one unusual, and potentially valuable, task: Using two of its six conical wheels, it excavated a trench to a depth of about 30 centimeters (12 inches). The Red Team back at the command site did not have time to use the imaging system to analyze the trench wall, but the Green Team on site reported that sedimentary layers were visible in the wind-deposited sand.

The Russians also had specialized scientific tasks to carry out. For example, they tested the rover's ability to deploy a large rectangular electromagnetic-sounding antenna on the ground. On Mars, this could be used to search for subsurface water.

With the more capable equipment at its disposal, the Lunar Team was able to perform a more refined geological analysis of the simulated landing site. Team members were also able to drive the rover satisfactorily using telepresence. That is, the imaging systems provided enough information for the team to drive the rover across the terrain in near "real time." The telepresence simulation was much more laborious for the Mars teams, who had to contend with a longer delay between a command and a response.

In Mars exploration, instant gratification will have to wait for further development in the field of virtual reality. Using this technique, the rover will survey the surrounding terrain, collecting data on such things as topography and surface color. A computer on Earth will take these data and prepare a three-dimensional color map of the area.

Then we send in the virtual rover—a three-dimensional model that exists only in the computer—to explore the virtual terrain. The operator will select a target for investigation and then attempt to drive the rover over to it. Only when the operator has found a safe path to the target will the real rover be commanded to move.

Connecting the Mars Rover's command system to the virtual reality model under development at Ames Research Center is still a job for the future. During these tests, we did generate a preliminary three-dimensional map of the Amboy terrain on a Silicon Graphics workstation, and using this we could drive the virtual rover.

Bring on the Public

We timed these tests to coincide with the National Science Teachers Association's annual convention, held this year in Anaheim, California. For the shake-down phase of testing, we set up the command center at McDonnell Douglas in the nearby town of Huntington Beach. For the next phase, we moved to a hotel across from the Convention Center. We invited the teachers, along with Planetary Society members, to watch us test the rover. Hundreds came.

NASA Administrator Dan Goldin also came and spent 35 minutes driving the rover across the lava field. We linked up with Mission Control at Johnson Space Center in Houston, and George Abbey, the assistant center director, was able to command the rover from there. *Apollo* astronaut Pete Conrad, now a McDonnell Douglas vice president, also took a remotely controlled turn around the Amboy lava field.

Lessons for Next Time

As much as we accomplished with these tests, we were not completely satisfied with the results. We tried to do too much in too little time. Not every task planned got completed. But there will be other chances.

Working with our Russian partners, McDonnell Douglas, NASA Ames and the science team, we are now planning our test program for next year. This one could be the most spectacular one yet! Stay in touch, and when we've firmed up the logistics, we'll let all our members know what's next for the Mars Rover.

Charlene M. Anderson is Director of Publications of The Planetary Society.

Thanks for the Support

These tests were made possible with the support of many people and organizations. In addition to our members, we thank L.A. Cellular, NASA, Odetics, Omni *magazine, Sense8, Silicon Graphics, Inc., and StereoGraphics Corporation.*

News and Reviews

by Clark R. Chapman

Just a hundred years ago, astronomer Percival Lowell founded an observatory, which he named for himself, on Mars Hill in Flagstaff, Arizona. Among the many discoveries made at Lowell Observatory during the subsequent century, the most famous is certainly Clyde Tombaugh's 1930 discovery of the planet Pluto. As years pass with no other large worlds revealing themselves in the dim outer reaches of the solar system, it is ever more likely that Pluto will prove to have been the final addition to our pantheon of nine planets (regardless of pointless attempts to demote Pluto's status; see the debate in the August *Sky & Telescope* about whether Pluto is a planet).

It is fitting that Lowell Observatory recently celebrated its centennial in part by hosting a scientific symposium entitled "Completing the Inventory of the Solar System" (June 27–30). It was long thought that the major planets and their moons all move in predictable, clocklike orbits, and that only a sprinkling of incidental asteroids and comets (plus Saturn's shining ring) rounded out this simple picture of our planetary system. But that turned out not to be the case.

Chaos: Natural and Man-made

As our computers have grown ever more capable of integrating the orbits of the planets back 4.5 billion years, so that we might see what the configuration was then, planetary motions have grown correspondingly more elusive. Chaos now seems rampant in nature, and the planetary clockworks have vanished as a useful concept. No planetary scientist expects planets to suddenly leave their orbits and hurtle toward us, but much of what happens in the solar neighborhood is chaotically unpredictable. Carl Sagan, in an evening lecture during the Flagstaff event, noted that we human beings may be introducing the most dangerous chaos of all as we contemplate moving asteroids around so that they miss Earth—or, if a neo-Hitler were in charge, perhaps *hit* Earth.

Modern instrumentation has revealed a wealth of additional objects—and whole classes of objects—that populate the solar system. They include all manner of rings, co-orbital satellites, a moonlet orbiting the asteroid Ida, split comets, and a dust cloud hovering behind our own planet. At the Lowell symposium, Eugene Shoemaker described the Trojan asteroids as an enormous population of careening objects that is not much smaller than the main asteroid belt. (Trojans are loosely confined in regions of space roughly 60 degrees ahead of, and behind, Jupiter in Jupiter's orbit.) Both asteroids and Trojans together pale in comparison with recently discovered Kuiper belt bodies beyond Neptune's orbit. Thirteen of these immense "comets" have been catalogued in just a few years, and their total mass could exceed that of Pluto, our Moon and all other planetary satellites combined.

The discovery about two years ago of a martian Trojan reminds us that there are many dynamical niches left in the solar system for new classes of objects. "Vulcanoids" may orbit the Sun inside Mercury's orbit. A stable zone for heliocentric bodies may exist between the orbits of Earth and Mars. Several weird objects found in the chaotic outer solar system (like the red-black body called Pholus) are surely just the tip of the iceberg. Meanwhile, the outer Kuiper belt and the Oort cloud remain terra incognita—but soon our instruments will begin to unveil that overwhelmingly dominant portion of the solar system's volume.

Celestial Suicides

Not only have new populations of bodies been found, but the Lowell symposium dramatized our changing perspectives about how the familiar members of the solar system behave. It now seems common for comets to become temporary satellites of Jupiter, and many may be tidally disrupted by passing close to the giant planet. Shoemaker-Levy 9's suicide plunge immediately following such disruption remains exceptional, however. Yet who would have thought that half of all Earth-approaching asteroids end their existence by diving straight into the Sun?! That was just one of several new ideas reported in Flagstaff based on exercising state-of-the-art computers.

As new telescopes, detectors and automated search procedures push the limits of completeness to ever smaller objects and ever greater distances, we are sure to uncover more remarkable attributes of our solar system. Meanwhile, the newly refurbished Hubble Space Telescope is showing us, with unprecedented clarity, solar system analogues of forming and evolving systems of dust and debris around other stars. Clear detection of planets like Earth or Jupiter orbiting Sun-like stars remains elusive—but not for long.

Lowell Observatory intends to remain a major player in completing the inventory of the solar system. For instance, it is involved in developing a new asteroid-search telescope as well as an optical interferometer that will surely yield important discoveries, even if there is no Planet X. This remarkable private observatory, still partly supported by the Lowell trust funds, is worth a visit if you are exploring the environs of the Grand Canyon and Meteor Crater. Its wonderful new visitor center, just completed for the centennial, is worth a visit all by itself.

Clark R. Chapman, a planetary scientist in Tucson, Arizona, has been our columnist since volume 1, number 1 of The Planetary Report.

World Watch

by Louis D. Friedman

Washington, DC—The NASA budget came out of Congress better than it was when it went in. Despite, or perhaps because of, dire warnings about choosing between space science and the space station, the 1995 administration request for both science *and* the space station was granted in full.

The science budget included full funding for *Cassini* and for the Advanced X-ray Astrophysics Facility, both of which had been threatened earlier in the budget process. It also included the new start for Mars Surveyor, which our members played an active role in supporting. Our efforts on behalf of the new program were widely noticed and acknowledged by members of Congress.

The space station plan was accepted by Congress in a dramatic vote in the House of Representatives in late June. Last year, key issues regarding the space station were decided by fewer than 10 votes (in one case, by a one-vote margin), but this year the margin was over 120 votes. What made the difference was the Clinton administration's decision to link the space station to its global stability objectives, especially with regard to Russia. Russia's participation in an international space station provides money and jobs for its aerospace industry and also for the United States'. Russia's experience in human spaceflight and in large boosters will also benefit the space station program.

NASA Administrator Dan Goldin led the efforts to convince Congress to support the administration's budget request for NASA, meeting with almost all representatives and senators to discuss the NASA program. He also personally shaped the two new starts, Mars Surveyor and "smallsat," in the image of his "cheaper, faster, better" philosophy.

Two programs strongly supported by The Planetary Society, Mars Surveyor and the Pluto Fast Flyby, both received endorsements in a new agreement signed by US Vice President Al Gore and Russian Prime Minister Viktor Chernomyrdin (see page 14). The Clinton administration also provided a great morale boost to supporters of space exploration by celebrating the 25th anniversary of the first human lunar landing. A White House ceremony honoring the *Apollo 11* astronauts was held on July 20, 1994, in the East Room. Society President Carl Sagan and Executive Director Louis Friedman were among the guests at the ceremony.

Washington, DC—In addition to the White House ceremony noted above, the *Apollo* anniversary was commemorated at a gala formal dinner put on by The Planetary Society and the National Space Society. At the dinner, The Planetary Society presented the first Thomas O. Paine Memorial Award for the Advancement of Human Exploration of Mars to NASA scientist Chris McKay (who is also the longtime coordinator of the Society's Mars Institute). A special award was presented to NASA Administrator Dan Goldin.

Vice President Al Gore attended the dinner. He and Society President Carl Sagan spoke on the legacy of *Apollo.*

Paris and Tokyo—Lunar initiatives, perhaps spurred on by the 25th anniversary of *Apollo 11*, are beginning to take shape in many of the spacefaring nations that have not yet sent spacecraft to the Moon. The European Space Agency announced that it was working on a plan (not yet approved) to establish a lunar base. Although a long-range goal of establishing a permanent crewed base by 2020 is mentioned, the plan starts small, with a 100-to-200-kilogram lander possibly launched in 2001. The lander would include experiments specifically designed to help plan a human-occupied base. Its projected cost is about $350 million. ESA is inviting international participation in this plan.

Japan, meanwhile, is the only nation with an approved lunar mission: Lunar-A, scheduled for launch in mid-1997. The mission will be launched on the new M5 booster being developed by the Institute for Space and Astronautical Sciences (ISAS). Penetrators carried on the spacecraft will sample subsurface lunar material. This mission could be the first planetary application of the penetrator technology, long under development in Russia and the US.

Beyond 1997, Japanese scientists at the high-level government Space Activities Commission, ISAS and the National Space Development Agency (NASDA) are considering lunar rovers, landers and other robotic devices for a lunar base after the year 2020.

Louis D. Friedman is Executive Director of The Planetary Society.

Questions and Answers

I recently noticed on a map of Venus that the highest point (about 7 miles above the mean) is in the Maxwell Montes region at 64 degrees latitude and 4 degrees longitude. I also noticed that this point has no name. To me that's like having a map name the Himalayas without giving a name to Mount Everest.

Why no name?

—Webb Masten,
Shelby, North Carolina

The most elevated region on Venus, called Maxwell Montes, is named after the Scottish physicist who first proposed the existence of electromagnetic radiation: James Clerk Maxwell, in recognition of the vital role played by radio and radar techniques in studying the cloud-shrouded surface of Venus. This region is one of only three features on Venus whose names predate the decision by the International Astronomical Union Working Group on Planetary System Nomenclature in the early 1970s to commemorate only female personages (both mythical and real) on that planet. These early names were kept because they had already been used in a number of scientific papers; in legal jargon, they were "grandfathered."

As the plural term "Montes" implies, the Maxwell feature comprises a range of mountains. The reason that names have not yet been assigned to specific peaks is that the mapping of this area is not judged sufficiently reliable to be sure of the true local topography. The area is topographically complex, and many of the details within it have not been sorted out. We hope that stereoscopic images obtained in the closing days of the *Magellan* radar mapping mission will allow construction of an accurate relief map of the Maxwell region.

—GORDON H. PETTINGILL,
Massachusetts Institute of Technology Center for Space Research

Factinos

Scientists at the Jet Propulsion Laboratory and the National Astronomy and Ionosphere Center in Arecibo, Puerto Rico, report in a May issue of *Nature* that they have found more evidence that Mercury may be hoarding secret caches of ice in its deep, perpetually dark craters. The researchers used radar to zero in on patches of what looks like frozen water inside craters at the planet's north and south poles.

Duane Muhleman of the California Institute of Technology first proposed the ice theory over two years ago when he found radar reflections at Mercury's poles that looked much like the type obtained by bouncing radar off Mars' ice-encrusted poles. "The most interesting aspect is that we believe ice has been there for probably billions of years. It probably contains a chemical history of the inner part of our solar system," Muhleman said.

The presence of ice also indicates that there may have been more water, carbon dioxide and other volatiles close to the newborn Sun, said Martin Slade, a JPL scientist and one of the authors of the *Nature* paper.

—from Elizabeth Wilson in the Pasadena *Star-News*

❖

More possible evidence for the existence of planets around stars other than our Sun has been uncovered by French astronomers examining new infrared images of the dust disk around the star Beta Pictoris, about 52 light-years away.

The researchers did not see any planets, but they did find what they think is the gravitational footprint of at least one substantial planet around the star. The inner region of the dust disk around Beta Pictoris appears to be swept clear of particles, indicating the possible effect of an orbiting planet.

The observations were conducted with a powerful infrared camera developed by the Astrophysics Service at Saclay, near Paris, and attached to a telescope at the European Southern Observatory in Chile. The scientists found the broad, dust-free region to be within 3.7 billion miles of the star, which also happens to be Pluto's distance from our Sun.

—from John Noble Wilford in *The New York Times*

❖

With the help of the Hubble Space Telescope (HST), C. Robert O'Dell, an astronomer from Rice University in Houston, Texas, has uncovered the strongest evidence yet that the process that may form planets is common in the universe. The scientist reported

Some companies are talking about putting rovers on the Moon and then renting them in a telepresence mode for fun and games. Others are talking about mining the lunar surface.

What law applies to companies working on the Moon? Who decides guilt or innocence if the parties conflict? What pollution laws are in effect to stop companies from polluting the surface and turning the Moon into a garbage dump? I hope we are not depending on the altruism of the companies!

—Glen P. Davies,
Calgary, Alberta, Canada

The short answer to your question concerning what law applies to companies on the Moon is "not much." The 1967 Outer Space Treaty prohibits national appropriation (sovereignty) of lunar territory, but does not outlaw private property rights. There is very little international law that would govern the activities of companies on the Moon by its own force: Virtually all international space law is directed at countries, not companies. However, the Outer Space Treaty does prohibit the "harmful contamination" of the Moon and other planets, which would seem to put some limits on "turning the Moon into a garbage dump."

The treaty also requires nations to supervise the activities of their nationals, so United States law and regulation would govern the operation of US companies on the Moon, while, say, Japanese companies would be governed by Japanese law. Where conflict develops between nationals of two countries, resolving it would become a diplomatic issue between the governments involved, or perhaps a subject for litigation in the World Court.

There is another treaty in existence, the 1979 Moon Treaty, which would do much more, including addressing questions of property rights and property protection. However, largely because it would do too much, the treaty has not been ratified by any space-going power.

—GLENN REYNOLDS,
University of Tennessee at Knoxville

I've heard that the film from past planetary exploration missions is deteriorating in storage in the national archives. Would it be possible to send it to space in order to prolong its shelf life until a process is developed to restore the film? Would space keep it intact?

—Timothy N. Chittum,
Buena Vista, Virginia

Radiation in space would actually damage the film. It's safer here on Earth. X rays and particle radiation were discovered early on because such radiation darkens film.

—JAMES D. BURKE,
Technical Editor

that observations with the newly repaired telescope clearly reveal that great disks of dust (the raw material for new planets) are swirling around at least half of the stars in the Orion nebula, a region only 1,500 light-years from Earth where new stars are being born (see photos at right).

O'Dell and a colleague, Zheng Wen, now at the University of Kentucky, surveyed 110 stars and found disks around 56 of them. "Since it's easier to detect the star than the disk, it's likely that far more stars are being orbited by protoplanetary material," he said.

—from NASA

These circumstellar disks in the Orion nebula are the strongest evidence yet that many young stars carry the seeds of future planets.

Photographs: C.R. O'Dell, Rice University/NASA

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The Making of a Soviet Scientist: My Adventures in Nuclear Fusion and Space From Stalin to Star Wars

By Roald Z. Sagdeev;
Wiley, New York, 1994, 339 pages.
Retail price: $24.95
Member price: $22.00

During that rapidly receding period known as the Cold War, a through-the-looking-glass world existed in the Soviet Union, where euphemisms abounded and the Ministry of General Machine Building meant the space program. In that universe, scientists led privileged lives and had mentors whose names are for the most part unknown in the West—with the possible exception of Andrei Sakharov, who won fame for his political dissent and not his science.

Planetary Society advisor Roald Sagdeev, a highly gifted experimental physicist, was born into that world in 1932. In an insightful introduction, Carl Sagan points out that, as a Tatar, Sagdeev was always an outsider and so especially sensitive to the way other outsiders, such as Jews, were arbitrarily treated by the system.

As a scientist, Sagdeev was frustrated by that system, in which individuals were pawns and no built-in mechanism for checks and balances existed. Yet Sagdeev managed to make that system work for him, vaulting from success in research (he was elected to the Soviet Academy of Sciences at the age of 36) to become head of the Soviet Academy of Sciences' Space Research Institute in 1973.

In that role, Sagdeev came to know many Americans, including Susan Eisenhower, President Dwight D. Eisenhower's granddaughter, to whom he is now married and who edited this remarkable scientific memoir. While scarcely mentioning his private life, Sagdeev does explain his emigration from the Soviet Union to the United States as a product of "heart drain" rather than "brain drain." He is now a professor of physics at the University of Maryland.

The Space Research Institute was responsible for the robotic exploration of the solar system. When Sagdeev took over, he found it rife with incompetence so outrageous as to be comic. What is truly remarkable, and a measure of his administrative talents, is that the program succeeded as much as it did.

Sagdeev kept the robotic space program alive by convincing the military that the missions to Venus and Halley's Comet would show the world that the Soviets had the same sophisticated technology as the Americans and could, by analogy, make multiple independently targetable warheads. What the rest of the world did not know was that the Soviet space program was extraordinarily backward technologically, especially in the realm of computing.

Sagdeev delights in describing his triumphs, and attributes his mastery of this special kind of diplomacy to the examples of men like the physicist Peter Kapitsa, who carried on a one-way correspondence with Stalin for years. Kapitsa was able to save individuals and shape programs, but once suffered internal exile for suggesting that the infamous head of the secret police, Lavrenti Beria, was unfit to run the atomic bomb program.

Early in his career, when he was transferred against his wishes to the Soviet counterpart of Los Alamos, Sagdeev began to think of himself as "a kind of intellectual serf." In spite of that feeling, he managed to maintain his integrity within the system by wit and sleight of hand.

He examines his own actions, and recalls the actions of others. The result is a frank, often amusing but ultimately devastating account of what the Soviet system was. In the end, it was responsible for its own destruction.

—Reviewed by Bettyann Kevles

Still Available:
Stardust to Planets: A Geological Tour of the Solar System

By Harry Y. McSween, Jr.
Take a quirky cruise by the planets with an idiosyncratic geologist who's willing to share the excitement he feels for our neighboring worlds.
(Reviewed May/June 1994.)
Retail price: $22.95
Member price: $20.00

Moon Shot: The Inside Story of America's Race to the Moon

By Alan Shepard and Deke Slayton.
The story of *Apollo* and the euphoria, achievements and disappointments of the early days of the space program as told by two of the original *Mercury* Seven astronauts.
(Reviewed July/August 1994.)
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Society News

Searching for Intelligence in the Midst of War

This past spring, while mortar shells and ethnic conflict were tearing their homeland apart, a group of students in the former Yugoslavia calmly pursued their studies of the Search for Extraterrestrial Intelligence. Inspired by *The Planetary Report* and Carl Sagan's *Cosmos,* seventh-graders in Subotica continued to explore astronomy and promote SETI.

According to one of the students, István Újfalusi, this informal group has been successful in getting a high school to include SETI in its curriculum. The group has also produced a video called *The Circle of Knowledge,* an examination of how life and intelligence developed.

Praising the students' efforts as remarkable, Planetary Society Executive Director Louis D. Friedman has given them a number of SETI-related books and materials to help them in this endeavor.
—CMA

Society Supports Ohio State SETI Program

The Society has restated its commitment to the Search for Extraterrestrial Intelligence with a grant to the North American Astrophysical Observatory. Using the Ohio State University radio telescope in Columbus, scientists will be able to continue the SETI Phase II data analysis project, a survey of radio signals that might have an extraterrestrial origin.

In light of NASA's recent loss of support for its SETI program, the Society's grant is especially important. The observatory will use the funds to complete an analysis and summary of the signals obtained by its Phase II survey.
—Louis D. Friedman, Executive Director

A Gathering of Minds to Explore the Planets

From October 31 through November 4, some of the brightest minds in planetary science will gather in the Washington, DC, area for the 26th annual meeting of the Division for Planetary Sciences of the American Astronomical Society.

The meeting itself will be held in suburban Bethesda, Maryland, and once again The Planetary Society will sponsor a public lecture. For more information, contact me at Society headquarters.
—Susan Lendroth, Manager of Events and Communications

Society Strengthens Ties to Japan's Young Astronaut Club

The Young Astronaut Club of Japan has begun publishing condensed versions of selected articles from *The Planetary Report* in *L5,* a monthly publication for its members. These articles are translated into Japanese and include many of the original articles' photographs.

On August 6, 1994, Bruce Murray, vice president of the Society, was a featured speaker at the club's International Jamboree in Iwate, Japan. Murray spoke about remote sensing technology as a "window to the future."

For more information, write to YAC Japan, Kabuto-cho, the 6th Hayama Building 3F, 17-2 Nihombashi Kabuto-cho, Chuo-ku Tokyo 103. You may also contact the club by telephone at 3-3669-7480, or by fax at 3-3669-7655. *—SL*

First Annual Thomas O. Paine Award Honors Goldin and McKay

In Washington, DC, on July 20—the 25th anniversary of *Apollo 11*'s landing on the Moon—NASA Administrator Daniel S. Goldin and scientist Christopher P. McKay received the first Thomas O. Paine Memorial Award for the Advancement of Human Exploration of Mars.

Goldin received the award (a memorial plaque, a certificate and a Mars flag) in recognition of his leadership of NASA, his emphasis on the importance of international cooperation in space and his preparation for the eventual human exploration of other worlds.

Now working at NASA's Ames Research Center, McKay received the award for his contribution to a better understanding of the possibilities of life on Mars. McKay's award also included a $5,000 cash prize to assist him in continuing his work.

The Planetary Society and the National Space Society organized the dinner at which the awards were given. Among the evening's speakers were Vice President Al Gore, astronaut Buzz Aldrin and Planetary Society President Carl Sagan. Hugh Downs, chairman of the NSS Board of Governors, was the master of ceremonies.

The Planetary Society is now seeking nominations for next year's Paine Award. Again, the award will go to the group or individual who has done the most to advance the long-range human exploration of Mars. The deadline for nominations is December 30, 1994. For an application and more information, write to Society headquarters, 65 North Catalina Avenue, Pasadena, CA 91106-2301; phone (818) 793-5100.
—Charlene M. Anderson, Director of Publications

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Mysterious Pluto is the smallest and coldest planet in our solar system. It also has the most eccentric orbit and a very large moon half its size. In "Pluto and Charon," by David Egge, that moon, Charon, is a silvery crescent above the horizon. Pluto's orbit is now taking it farther from the Sun, and the planet is becoming colder as it goes. If no spacecraft visits this tiny world in the next 25 years, before its thin atmosphere freezes onto its surface, we may have to wait another two centuries.

David Egge is an astronomical artist who lives in Minneapolis, Minnesota. His work has appeared in *Omni, Astronomy, Science Digest* and other publications, and on the *Cosmos* television series.

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