The PLANETARY REPORT

Volume XVII Number 4 July/August 1997

The Allure of Io

Table of Contents

Volume XVII

Number 4

July/August 1997

Features

4 Io and I

Sometimes scientists develop personal relationships with the objects they study, and this is the case with astronomer John Spencer and Io, Jupiter's volcanic moon. Since he was a child, looking through a backyard telescope, this speck in the sky has intrigued John, and he has been fortunate enough to live in the time that that speck became a knowable world through advances in telescope technology and visits by robotic explorers.

9 First Reconnaissance: Exploring Other Solar Systems

Since Greek philosophers first pondered the possibility that other stars possessed worlds like our own, the question of extrasolar planets has intrigued astronomers. Indeed, in the past few decades they have actively pursued better ways to carry out the search. Suddenly, technology has caught up with speculation, and other solar systems are being discovered and studied on an almost regular basis. Here is the story of one of the most successful search programs now under way.

14 Tribute to Clyde Tombaugh

In all history through 1995, there were only three planets discovered. Some of us were fortunate enough to know one of the discoverers, Clyde Tombaugh, who died earlier this year. David Levy, himself the discoverer of several comets, including Shoemaker-Levy 9, recounts some of the highlights of Clyde's productive life and shares a few memories.

15 Growing the Planetary Society: New Advisory Council Formed

Carl Sagan's death has prompted many changes in the Planetary Society, and some of them, we hope, will make our organization even stronger and more effective. One change that can add both energy and impetus to our efforts is the reconstitution of the Board of Advisors into the Advisory Council. Its new chair, John Logsdon, an eminent space policy historian and long-time Society supporter, shares his hopes for the new council.

Departments

3 Members' Dialogue

16 Basics of Spaceflight

18 News & Reviews

19 World Watch

20 Questions and Answers

22 Society News

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On the Cover:

A ring of fresh, bright red material encircles Pele, an almost continuously erupting volcano on Jupiter's moon Io. From this angle, Pele's plume is nearly invisible, but deposits indicate that it spews sulfurous materials out to more than 600 kilometers (400 miles) from its central vent. Another bright red deposit lies next to the volcano Marduk. Such deposits darken and disappear within years or decades, so the presence of bright red materials marks the sites of recent eruptions.

This false-color infrared image is a composite made from data taken on *Galileo*'s first orbit of Jupiter in June 1996 and its third orbit in November 1996. It covers an area almost 2,400 kilometers (1,500 miles) across. North is to the right of the picture.

Image: Paul Geissler and Alfred McEwen, Lunar and Planetary Laboratory, University of Arizona

From The Editor

Spacecraft exploration has always been the focus of the Planetary Society, and it will be as long as humanity sends robotic emissaries—and human explorers—out among the planets. But our knowledge of other worlds comes from many sources. Historically, the most important has been Earth-based telescopes.

Spacecraft and telescopes work synergistically to open up worlds around us, and this is a subtle theme behind two major features in this issue. In the case of "Io and I," the volcanoes were discovered by *Voyager*, studied between missions by telescope, and now are being visited by *Galileo*. For "First Reconnaissance," the existence of extrasolar planets became apparent through telescopic observation. To see an Earth-like planet around another star, however, will require space-based technology, possibly a telescope-spacecraft hybrid parked out near Jupiter.

Planetary exploration is a complex yet exciting endeavor; it takes both great commitment and resources to accomplish. The rewards are correspondingly great. It is our work at the Society to ensure that the will to explore is fulfilled.

—Charlene M. Anderson

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Members' Dialogue

Carl Sagan Remembered

Congratulations on an issue that represented the many facets of Carl Sagan so well. At the Jet Propulsion Laboratory's Multimission Image Processing Laboratory we have many fond memories of Carl. I will never forget the look on his face as the first high-resolution imagery of Phobos appeared on our primitive displays during the *Mariner 9* mission. His excitement and enthusiasm invigorated a group of JPL people who had been working some long and difficult hours. He later often told his story of how, up until that time, Phobos had been seen only as a dot on an astronomical plate or in the eyepiece of a telescope, and how excited he was to be living in the time when our perception of Phobos was changed forever by viewing a set of high-resolution imagery acquired by the reconnaissance missions he advocated so strongly.

That infectious excitement helped inspire a generation of people who worked at processing image data on *Mariner*, *Viking*, *Voyager*, and *Galileo*. We will miss his physical presence as we move on to future missions, but his spirit will always be there as the story continues to unfold.

—WILLIAM GREEN,
Granada Hills

As an undergraduate at Cornell University in the early 1970s, I had the privilege of attending many of Carl Sagan's lectures. Recently, as a college instructor, I had the opportunity to attend his commemoration this past February in Pasadena. As motivating as it was to hear him in person, I found that this was not a sad event but rather an uplifting experience—one that further enlightened me to his vision, his greatness, and his passion for educating those who may have never ventured to think about our "Pale Blue Dot" and the possible existence of our cosmic neighbors. "Carl Sagan, Teacher" (see the May/June *Planetary Report*) epitomized why I chose to do what I now do best. He was my hero in a time when heroes are rare and their influence is finite.

My becoming a member of the Planetary Society was not a choice but rather a need to carry on his dream by associating myself with what he believed in. Sagan had an influence on millions of people throughout the world, but to this one earthling his influence was far-reaching, for he used his scientific thought to leave many disciples to carry on his greatness.

—JOEL GREENBERG,
Pasadena, California

Humans Versus Robots

In the May/June1997 issue of the *Planetary Report*, Louis Friedman suggests that a generally accepted rationale for sending humans to Mars does not yet exist. I find this strange since, if there has been no rationale, what could have persuaded our Society to support such a mission in the first place? I am one of those opposed to the idea of human missions to the planets.

Such missions are incompatible with planetary science for the simple reason that when people are sent into space, the first requirement is that they be brought back alive. Since this is true even for excursions into near space, it is not hard to imagine how much more dominant the question of safety would be for human missions to Mars. The inevitable result is that the amount of science done will be limited compared to what real Mars science would require. "Manned planetary science" verges on being an oxymoron. Human-crewed planetary missions, if they ever occur, will be more public entertainment than science. They will be inspired by the same attraction to danger that in an earlier age popularized gladiatorial combats between men and wild animals.

Because humans who go into space must carry a terrestrial environment with them, these missions are enormously expensive. If a fraction of the sums spent on putting people into space were spent instead on the development of exploratory robots—controlled by human beings on Earth—there is no doubt that the scientific study of Mars could be carried out not only "smaller, cheaper, faster," but also better than anything likely with astronauts.

—NORMAN H. HOROWITZ
Pasadena, California

Save Pioneer

After reading "Farewell, *Pioneer*" in the March/April 1997 issue of the *Planetary Report*, I'm left with a question. Even if budgetary constraints are imposing on our ability to to listen to what *Pioneer 10* is sending, I find it hard to fathom that *some* organization could not figure out a way to tap into this resource. But even if no one has the time, money, or energy to listen, why is it necessary to send an "irrevocable command to shut down"? What purpose does this serve other than to discard any future options we may have? If we quit listening for a while due to budgetary constraints, that's fine. But if we turn it off and then find a purpose and money to fund it, we've lost the opportunity.

—ROB FRITZ,
Lake Forest, California

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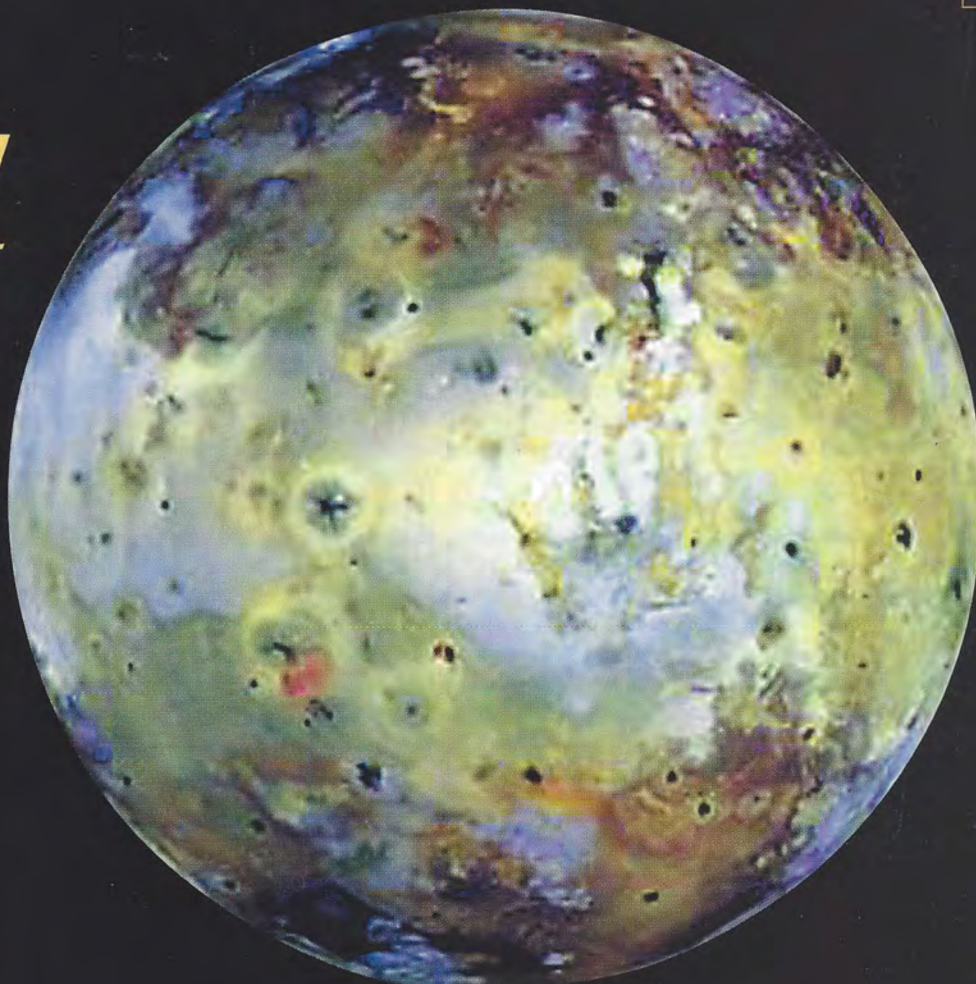
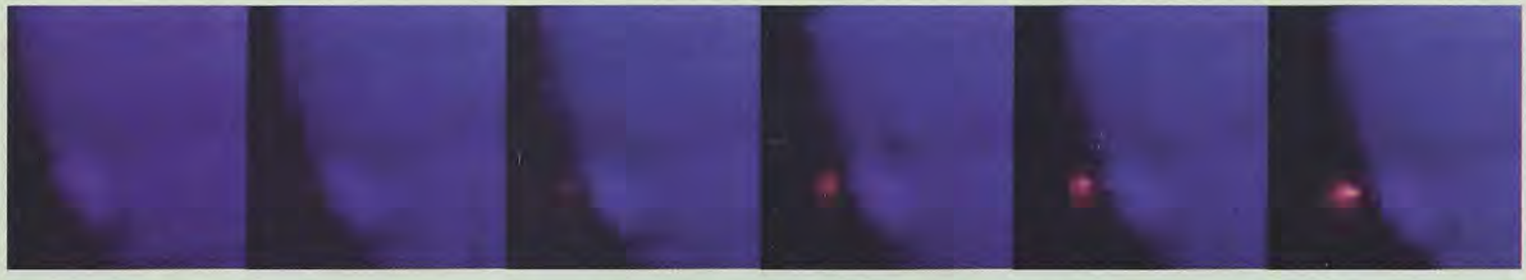
Io and I



by John Spencer

The author followed a lifelong fascination with the Jupiter system to a career as an astronomer at Lowell Observatory in Flagstaff, Arizona. Photo: Courtesy of John Spencer

In the spring of 1970, in Lancashire, England, a teenage boy (me) drags his indulgent visiting relatives out of the warm house into the back garden to show them something wonderful through his borrowed 3-inch telescope: the bright sparks of Jupiter's four big moons, arrayed on either side of the giant planet. In the spring of 1995, on the summit of Mauna Kea, Hawaii, a planetary astronomer (yes, me again) trains the 3-meter NASA Infrared Telescope on the strangest of those moons, volcanic Io, and sees an enormous eruption, bigger than any he has seen before, its brilliant infrared glow overwhelming Io's disk. This time, his audience is a bit larger,



Left: This is Io, a world ruled by volcanoes, which quickly wipe out other types of landforms, such as the impact craters that mark most solid bodies in our solar system. In this image, you can pick out features as small as 2.5 kilometers (1.6 miles) across. The dark features show up in Galileo*'s instruments as hot spots and are probably active lava flows. The colors here have been enhanced to bring out variations in color and brightness.* Galileo *obtained the color data at a range of 487,000 kilometers (303,000 miles). The color was then combined with high-resolution data taken at distances between 245,000 and 400,000 kilometers (152,000 and 249,000 miles).* Image: Lunar and Planetary Laboratory, University of Arizona; JPL/NASA

Above: It's volcano-rise on Io, as six volcanoes emerge in succession from behind the planet. The author took this sequence of images from an infrared telescope on the summit of an earthly volcano, Mauna Kea, on Hawaii. Infrared telescopes are great tools for observing Io, for they can pick out hot spots on the relatively cool surface of the moon. Images: John Spencer

for thousands of schoolchildren in North America and Europe, participants in the annual "Jason Project," are listening in and hearing about the discovery as it happens. But in each case, the sense of wonder inspired by the awesome Jupiter system, and the thrill of sharing that wonder with others, is the same.

Why do I find the Jupiter system so fascinating? Perhaps because it is the place where, as we move away from the Earth, things start to become seriously strange. Jupiter is near enough that it dominates our skies, and has been familiar to us since before we were human, and yet it is far enough away that the terrestrial rules no longer apply. Here's a planet with no surface, where multicolored storms rage for decades, with places where the rock is made of ice, where the metal is made of hydrogen, where the snow is made of sulfur dioxide, where moons come by the dozen, where the skies are full of strange glows and invisible, deadly blizzards of oxygen and sulfur atoms, where worlds are melted and comets torn apart by the force of gravity—all arrayed for our viewing pleasure, a mere half-billion miles away.

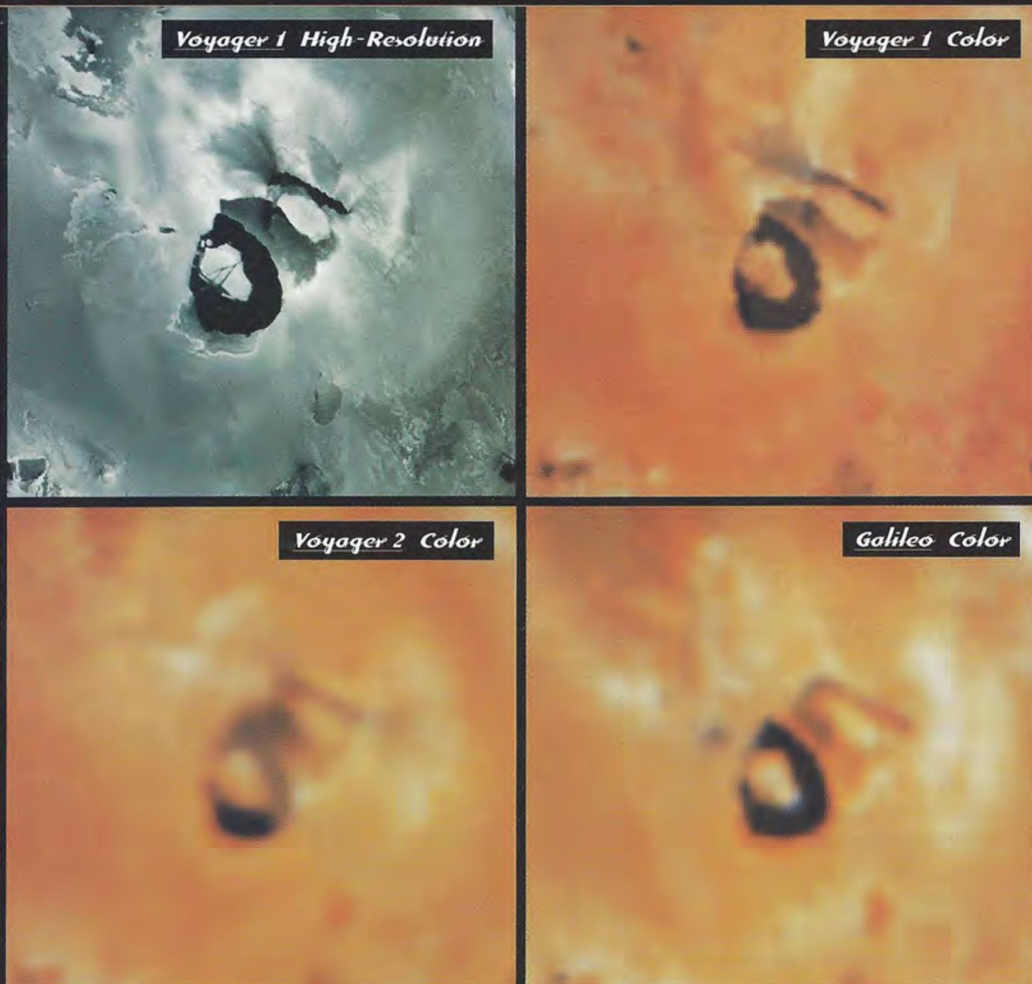
One world in the Jovian system has always grabbed my attention more than the rest—the bizarre moon Io. A victim of proximity to Jupiter, it is distorted and flexed so much by the giant planet's gravity that much of its interior is melted, and the surface of this moon seethes with volcanic activity. The volcanoes have covered the surface in volatile sulfur and oxygen, which are torn away from Io with the help of Jupiter's magnetic field and spread around Jupiter in glowing clouds.

Though Io has fascinated me since 1979, when the *Voyager* mission first revealed the moon's volcanoes, it took me a while to find a "niche" in which I could make my own scientific contribution. My dissertation work concentrated on Jupiter's other big moons. When I started a postdoctoral fellowship at the University of Hawaii in 1987, I seized the opportunity to team up with veteran Io observer Bill Sinton, who for a decade had been watching the infrared glow of Io's volcanoes from the NASA Infrared Telescope on Mauna Kea. We tried to continue the program, making a few improvements, but for a couple of years it seemed that whenever we went to the telescope, the clouds closed in. When the weather was clear, our equipment didn't work. We were also frustrated that while we could measure the general volcanic glow from Io (weather and equipment permitting), it was difficult to locate and identify individual volcanoes: Io is so small and far away that mostly all we could do was measure the total radiation from all the volcanoes. Only Loki, Io's largest volcano, could be distinguished on a regular basis, and that only by indirect techniques.

An Amateur's Ingenious Idea

Then in mid-1989, several things happened. At a small workshop in Pasadena devoted to Io, an amateur astronomer, John Westfall, suggested that perhaps you could tell where the volcanoes were on Io by timing when they disappeared behind Jupiter as Io passed behind the planet, a phenomenon called a Jupiter occultation. To our embarrassment, none of us professionals had thought of this, though it seemed as though the idea might work. At about the same time, the first infrared cameras were becoming available. These could take real infrared pictures of celestial objects, instead of just measuring the total amount of their radiation. Users of these cameras were reporting spectacularly sharp images from the telescopes on Mauna Kea, perhaps even sharp enough to see details on Io's tiny disk. Could we combine this new technology with Westfall's new idea, using an infrared camera to take pictures of Io that could locate individual volcanoes, and refining their positions further by timing their occultation by Jupiter? It seemed worth a try, so Bill and I put in a proposal to use the NASA Infrared Telescope's new infrared camera to look at Io in early 1990.

We got results sooner than we expected. In December 1989, as the team developing the new camera, led by Mark Shure, prepared for a test run on the NASA Infared Telescope, fellow Iophile Jay Goguen and I independently suggested that Io would make a good test target. On the third night of the tests, Io was due to disappear behind Jupiter, so we could also try the occultation technique. I decided to fly over to the Big Island for the third night only, to help out during the Jupiter occultation. On the first evening of the tests, I was just going to sleep at home in Honolulu when the phone rang. An excited Mark Shure was on the line from Mauna Kea. "We can see Loki!" he exclaimed. Mark and his team were lucky enough to have caught the volcano during a bright eruption, and the images were indeed sharp



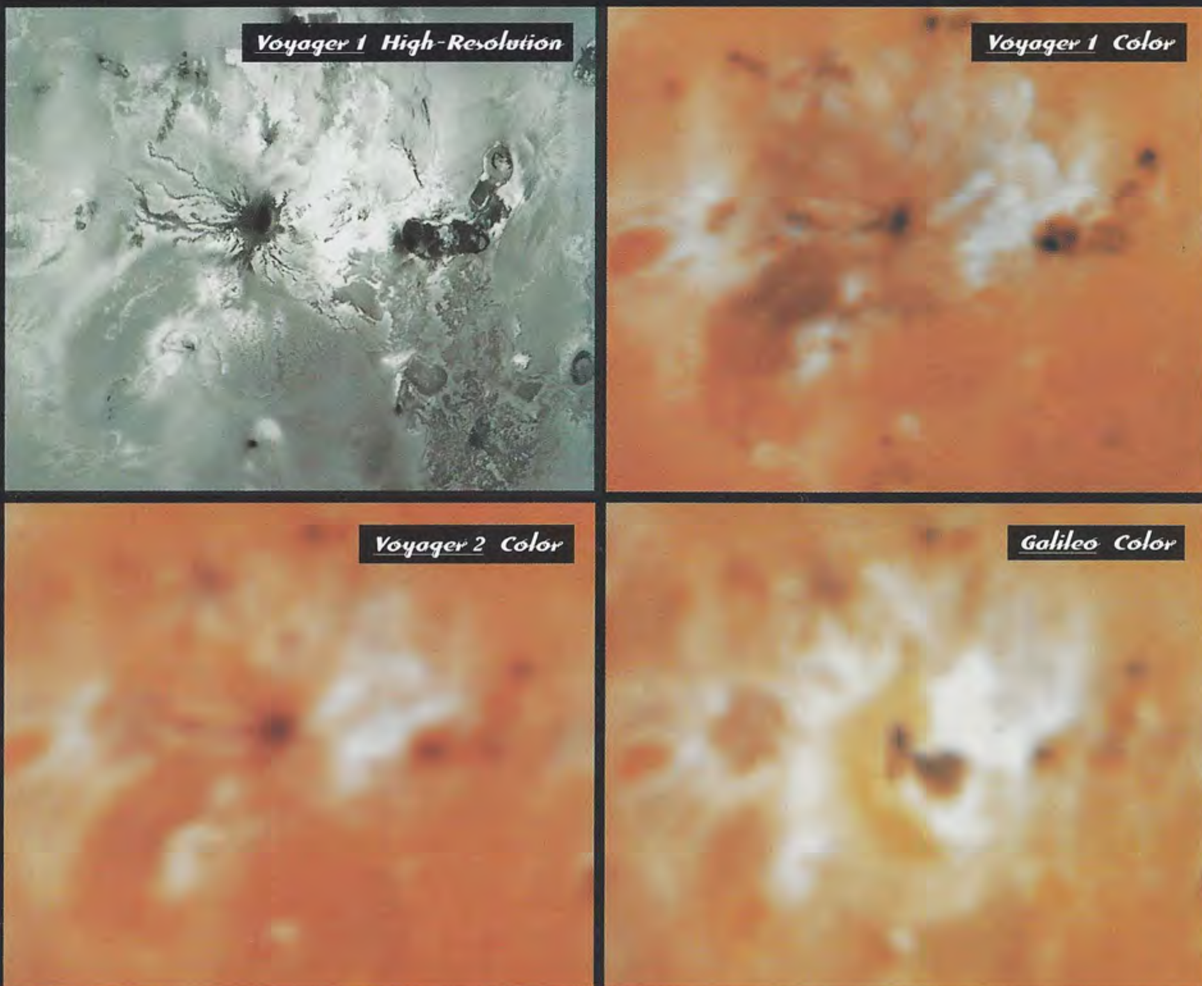
On the eve of Christmas Eve 1989, Loki Patera demonstrated for John Spencer that the occultation technique for pinpointing an Ionian volcano's position would work. Loki was a good partner in this research for it is the most active volcano on Io and can usually be counted on to put on a good show. But when Galileo *observed this region on June 27, 1996, the volcano was uncharacteristically quiet. During the* Voyager *encounters, dense plumes coming from the fissure to the northeast of the dark caldera obscured much of the surrounding terrain.* Galileo *saw no evidence of similar activity. These images cover a region 894 kilometers (556 miles) wide.*

enough to see it directly, as a bright point of light on Io's disk.

So it was with great anticipation that I flew to the Big Island two evenings later, the night of the Jupiter occultation. It was two days before Christmas, and Hilo airport was crowded with people coming over from Honolulu for the holidays. I drove from the airport past suburban houses garish with Christmas lights, then continued upward on the familiar mountain road, into the dark rain forests and open ranchlands that ring Mauna Kea. Progress was interrupted by a flat tire at about 8,000 feet, but I got a lift and finally reached the 13,500-foot summit, where Mark and his team were already at work. We turned the telescope to Io, and there it was: a crisply resolved disk, with Loki blazing forth in the northeast quadrant. In the rock-steady air of a perfect Mauna Kea night, we were seeing Io more clearly than anyone had since *Voyager*. Then, right on schedule, Io slid into Jupiter's shadow. Its disk disappeared into darkness, but Loki remained, a brilliant starlike point of light, glowing in the dark. Then, as Io continued on its orbit and began to pass behind the disk of Jupiter itself, Loki's glow held steady until it, too, swept behind the planet and suddenly winked out. John Westfall's occultation idea worked! We drove down the mountain in the dawn light of Christmas Eve exhilarated. It had been one of those rare and magical nights at the telescope when we had seen something that no one had ever seen before. We had watched the setting of a volcano behind a planet.

Thrill of Discovery

But more was to come. Back in Honolulu, after the New Year, I spent most of a frustrating Saturday afternoon struggling with a research project that didn't seem to be going anywhere. Looking for some relief, I decided to give the Io images a closer inspection. After running through the sequence of frames a few times, I thought I saw an extra point of light next to Loki, almost lost in the big volcano's glare. It disappeared behind Jupiter before Loki did. I gradually convinced myself that it was real and called a couple of other people into the office to get a second opinion. They agreed that, yes, something was there. It was a new volcano, never before seen! The images, combined with the disappearance time, allowed us to determine a fairly precise location, near a distinctive dark area in the *Voyager* images. I gave the newly discovered volcano the informal name Kanehekili, after a Hawaiian thunder god.



Eighteen years ago, the two Voyagers *flew by Io and discovered that this little orange moon is the most volcanically active object in our solar system. Since then, ground-based observers, like John Spencer, have watched Io carefully and have seen its face change. This series of images from spacecraft shows just how much the volcano Ra Patera has changed. Notice how, since 1979, dark materials have overflowed the walls of the summit caldera, moving out to the south and southeast. These images cover an area 953 kilometers (592 miles) wide. The* Galileo *image was taken on June 27, 1996 as the spacecraft made its first close flyby of Ganymede, looking past that moon to Io.*

Images: JPL/NASA

Now I was armed with two new and powerful techniques for studying Io's volcanoes: I could use the infrared camera and Mauna Kea's superbly steady air to see them directly, and I could locate them by timing their disappearance behind Jupiter. I finally had my "niche" and could contribute something unique to studies of my favorite moon. The opportunity could not have come at a better time: my temporary job at the University of Hawaii was nearing its end, and I needed something like this to establish myself as an independent scientist. I embarked on a program to take infrared images of Io as often as the telescope time allocation committee would let me, and I secured a NASA research grant to fund the studies. Since then I and my friends and colleagues have made more than a hundred movies of Io's occultations by Jupiter, from Mauna Kea and from my new home at Lowell Observatory in Flagstaff, Arizona. Sometimes visiting relatives join me at the telescope, continuing the tradition established in 1970.

There is always more to learn, because Io is always changing. Kanehekili and Loki continue to glow brightly for our cameras, at 1,000 degrees Fahrenheit or so, though Loki's brightness varies dramatically from season to season. Every so often these old standbys are dwarfed by brief, brilliant eruptions in other regions that last anywhere from a few days to a few months. These brief eruptions are sometimes so hot, up to 2,250 degrees Fahrenheit, that they may be violent "fire fountains" of molten rock.

Jupiter Watchers

We are far from being the only Io watchers. Bill Sinton has retired now, but several other groups, with their own unique "niches," also study Io's volcanoes. Other astronomers apply their ingenuity to observations of Io's surface composition, its tenuous sulfur dioxide atmosphere, the glowing clouds of sulfur, oxygen, and sodium that escape from Io, or to other dynamic aspects of the Jupiter system. We coordinate our efforts through an informal network called the "International Jupiter Watch," sharing data to discover, for instance, whether variations in the volcanic activity might cause variations in other phenomena. So far we haven't seen obvious cause-and-effect relationships, but we keep looking, and our efforts cross-fertilize in many other ways. Now that *Galileo* has joined the natural satellites in orbit around Jupiter, we can compare our results with the close-up reports

With its rugged mountains several kilometers high, picturesque plateaus of multilayered materials, and, for variety, low-lying volcanic calderas, Io might seem at first a very inviting landscape, until you consider that the dark, flow-like features could be lava erupting through the surface and that the bright areas are possibly deposits of sulfur-dioxide frost—not to mention the deadly Jovian radiation. On this world, volcanic eruptions occur so frequently that impact craters—the dominant landform on most moons—are rapidly obliterated by the molten materials spewing out of Io's interior.

This image covers an area about 2,000 kilometers (1,000 miles) wide, resolving features as small as 2.5 kilometers (1.6 miles). Galileo *took this image on November 6, 1996 from a distance of 245,719 kilometers (152,690 miles).*

Image: JPL/NASA

from the spacecraft, which is able to study Io in much more detail, though much less frequently, than we can from Earth. Our earthbound efforts can help with the planning of *Galileo*'s observations, and vice versa.

Volcanoes There and Here

Something that always delights me is that we base our study of extraterrestrial volcanoes on the summit of a dormant terrestrial volcano, Mauna Kea. As I drive down from the dark Hawaiian summit after an evening measuring Io's volcanic glow, I can often see the volcanic glow of the lavas of Kilauea, Earth's most active volcano, off in the distance to the southeast. Different planet, same process: a powerful reminder of the kinship among worlds of the solar system.

Given a chance to help illustrate this theme, I was thrilled to take part, in early 1995, in a series of television broadcasts that featured our Io volcano work alongside the work of terrestrial volcanologists who studied, on much closer terms, the flowing lavas of Kilauea. The broadcasts were part of the annual "Jason Project," the brainchild of oceanographer Robert Ballard. Every year the project puts out a series of live, interactive television shows for schoolchildren, showing scientists at work in a particular area, in this case the Big Island of Hawaii. Every morning for two weeks, weather permitting, my wife Jane and I, joined by telescope operator Dave Griep, drove up from the dormitory at 9,000 feet to the NASA Infrared Telescope, focused on Io, and reported hourly to the TV audience on what we were up to and what we could see. On the fourth day of the broadcasts, the fates smiled on us and there was a huge eruption on Io, one of the largest ever seen. (It happened to be my birthday, making this eruption one of my best-ever birthday presents.) I hope we were able to transmit our excitement to all those watching children, and I hope they caught something of the thrill of discovery that makes science such a uniquely exciting enterprise.

As I write, Earth's orbital motion is bringing Jupiter and Io back into view from behind the Sun, raising the curtain on the 1997 Io observing season. *Galileo*, on its sixth orbit of Jupiter, is also preparing for its next round of Io observations. No one knows what surprises Io will spring on us in 1997, but we can't wait to find out. ■

In a burst of sunlight, the plume of the erupting volcano Prometheus becomes visible to Galileo *as the spacecraft passes through Jupiter's shadow. The volcano lies just out of sight, beyond the edge of Io, but the 100-kilometer (60-mile) plume extends far enough to catch sunlight and scatter it into* Galileo*'s cameras. The sunlight also illuminates the cloud of sodium atoms that surrounds Io, spewed into space by the nearly nonstop eruptions.*

Galileo *took this image when it was 2.3 million kilometers (1.4 million miles) from Io on November 9, 1996.* *Image: JPL/NASA*

First Reconnaissance: Exploring Other Solar Systems

by Paul Butler

After 400 years of speculation, the reconnaissance for nearby planetary systems began on October 6, 1995. On that day the Swiss team of Michel Mayor and Didier Queloz announced that they had discovered a very strange planet orbiting the solar-type star 51 Pegasi. Over the subsequent two years, nine other planetary systems, both strange and familiar, have been uncovered.

Detecting an extrasolar planet is extremely difficult. Depending on its orbital distance, a Jupiter-mass planet is one hundred thousand to one billion times fainter than its parent star. Directly looking for extrasolar planets is like looking for a firefly in the glare of an atomic blast. Indirect techniques have therefore been developed to search for the subtle effects, primarily gravitational, that a planet has on its host star.

For most of this century the only viable means of detecting extrasolar planets has been precision astrometry. A star at 30 light-years with a Jupiter-like planet will wobble by about 1 milli-arc second, with a period of 12 years, relative to distant background stars. For comparison, 1 milli-arc second is the size of a quarter seen from 10,000 kilometers (6,000 miles) away. The magnitude of the wobble decreases with distance, so astrometry is most useful on the nearest stars. Current astrometric techniques are only able to measure the position of a star to a precision of about 1 milli-arc second, but development of optical interferometers could improve this precision by 10 to 100 times within the next few years (see Basics of Spaceflight, page 16).

The new technique of precision Doppler spectroscopy has accounted for all the extrasolar planets that have been discovered so far. An orbiting Jupiter-like planet will impel its host star to move in a small counter-orbit. Jupiter tugs the Sun with a velocity of 13 meters per second, slightly faster than human sprinting speed. The Doppler (or radial) velocity of a star will periodically change as the star moves toward and then away from the observer. This can be detected as a subtle periodic blue and red shift in the spectrum of the star. Historically Doppler velocity measurements have had errors of 1,000 meters per second or more. Beginning in 1980 Bruce Campbell and Gordon Walker pioneered a technique capable of measuring Doppler velocities to a precision of 15 meters per second (see the May/June 1988 *Planetary Report*). Currently five groups in North America and Europe are carrying out Doppler surveys of nearby stars with a precision of 20 meters per second or better.

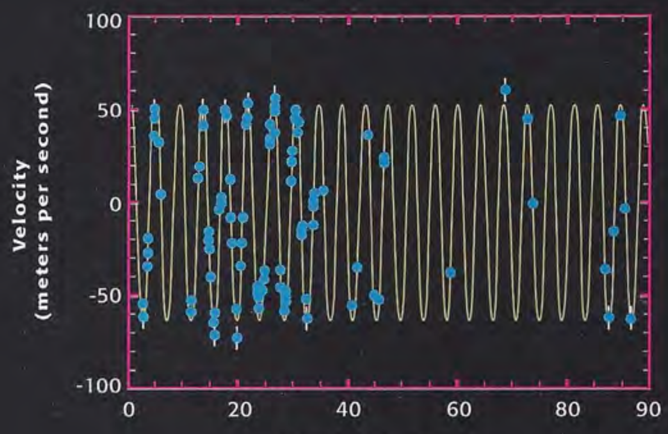
Building a Planet Detector

Of the extrasolar planets discovered to date, six have been found by Geoff Marcy and myself using the 3-meter telescope at Lick Observatory and an instrument we designed and built in the chemistry laboratories of San Francisco State University. In the summer of 1987 we began taking data. Over the last 10 years we have repeatedly monitored about 100 stars, searching for those that show the characteristic Doppler wobble of planetary motion.

During the first several years of the Lick Observatory Planet Search we were plagued with unexpectedly large measurement errors. Our calculations and simulations suggested that the information in each spectrum should yield a final precision of 10 meters per second, an expectation that was easily met in short-term tests. Over the course of a night the velocity variation, or scatter, from repeated observations of a star was typically 5 to 10 meters per second. The problem was that from night to night observations of a star would scatter by 20 to 100 meters per second.

The source of the long-term scatter was small changes in the point-spread-function of the spectrometer. If a

Figure 1: First Three Months of Doppler Velocities from 51 Pegasi



This is the signature of the first planet found around a Sun-like star. The distinctive sinuous shape of the data betrays the presence of an unseen companion tugging at its parent star, 51 Pegasi. The planet is about the same size as Jupiter, but it zooms around the star once every four days. In comparison, Jupiter takes nearly 12 years to orbit the Sun.

Figure 2: Distances of Planets from Host Star

The extrasolar planets found around Sun-like stars through the end of 1996 are all much more massive than Earth, and yet all but two orbit closer to their star than Earth does around the Sun. Before these discoveries, theorists held that extrasolar planetary systems would resemble our own. In planetary science, one learns to expect the unexpected. Charts: Paul Butler; modified by B. S. Smith

laser beam were sent into a perfect spectrometer, all the light from the laser would fall on a single spot on the spectrometer detector because a laser produces light of a single wavelength. In real-world spectrometers, the laser light forms a small spread-out blob at the spectrometer detector. The shape of this blob is the point-spread-function. To overcome these distortions, we spent six years writing a computer program that constructs complete models of each observation, pixel by pixel, accounting for both the intrinsic stellar and reference spectra, and of the spectrometer, in particular the troublesome point-spread-function.

In November 1994 Steve Vogt, who designed and built the high-resolution spectrometers at Lick and Keck observatories, replaced the existing camera on the Lick spectrometer with newly designed optics. His efforts tripled the resolution of the Lick spectrometer. As a result of the improvements to the camera and computer software, the velocity precision of the Lick project improved to 3 meters per second. This was a major breakthrough. For the first time it was technically possible to make a believable detection of a Jupiter-like planet orbiting another star. At this point all we needed to find planets was computer time. Our computers at that time would have required about four years to analyze the backlog of observations.

First Extrasolar Planet Confirmed

Three months later the Swiss team of Mayor and Queloz made their monumental announcement, the Sun-like star 51 Pegasi (51 Peg) had a planet of approximately one Jupiter-mass in a 4-day orbit. Mayor and Queloz had been surveying 142 stars for a year and a half using a specially designed super-stabilized "Doppler spectrometer," for which they had achieved a precision of 15 meters per second. Their technique did not require a sophisticated computer model of the spectrometer, allowing them to analyze their data immediately.

The orbital characteristics of the 51 Peg planet were completely unexpected. The 4.23-day orbital period implied that the planet was 20 times closer to its star than the Earth is to the Sun. Previously theorists had strongly argued that all planetary systems would look like the solar system, with small rocky planets in close and massive planets farther out. Because it was theoretically unexpected, and because of the abysmal history of previous claims of extrasolar planets, the media did not immediately pick up the story.

On October 11, five days after the Swiss announcement, Geoff Marcy and I began a four-night observing run at Lick Observatory. All four nights were clear. We took 27 observations of 51 Peg. All available computer resources were thrown at analyzing these observations, and by late Sunday evening, October 15, the results were in: 51 Peg had an absolutely sinusoidal (S-shaped) velocity wobble with just the period given by Mayor and Queloz. The Lick data were five times more precise than the Swiss data, allowing us to determine the orbital eccentricity. In their announcement paper, Mayor and Queloz had suggested that the 51 Peg system might have a second planet with an orbital period of one to two years. The more precise Lick data show that this second companion is a mirage due to long-term systematic errors in the Swiss technique. Figure 1 (above) gives the first three months of data on 51 Peg from the Lick program.

We began a desperate search for the necessary computer resources to analyze the more than eight years of data we had collected on our stars. In November 1995 three research groups at the University of California at Berkeley donated computer time, and two months later SUN Microsystems contributed two state-of-the-art ULTRAs. From November 1995 through the following April all of these computers were driven around the clock to clear out the years of backlogged data.

Of the 100 stars in the Lick survey, six initial candidates emerged. These six stars show Doppler velocity wobbles of 45 meters per second or more, much larger than the allowance for measurement errors. The critical feature that marks these wobbles as being planetary in nature is their shape. A wobble due to an orbiting planet must have exactly the shape required by the Laws of Planetary Motion, worked out by Johannes Kepler between 1603 and 1619.

Giant Planets in Tiny Orbits

All the known substellar companions with less than 10 times Jupiter's mass that orbit normal stars are portrayed in Figure 2 (left). [As we went to press, a Harvard team led by Bob Noyes announced the discovery of a 1.1 Jupiter-mass planet in a 40-day orbit around the star Rho Coronae Borealis. This discovery is not reflected in Figure 2.] These planets fall into three main groups. The largest group at the moment, with four members, is the "51 Peg" class of planets. These objects have orbital periods of 3.3 days to 2 weeks. In contrast the "speediest" planet in our solar system, Mercury, requires 88 days to complete an orbit. While Mercury is a rock with less than 1/5,000 of a Jupiter mass, the four 51 Peg-like planets have mass from one-half to four times that of Jupiter.

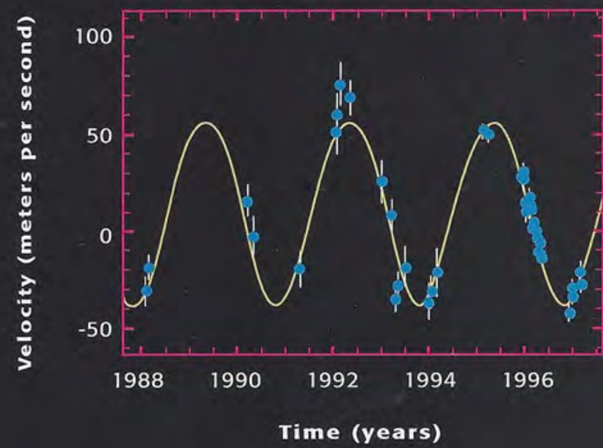
These planets probably have a Jupiter-like composition of hydrogen and helium gas, but they could conceivably be enormous rocks, colossal nickel-iron bowling balls. They orbit at a distance of only 10 to 20 stellar radii (Earth orbits at 200 solar radii, Jupiter at more than 1,000). As a result they are scorching hot, ranging from 1,000 to 1,700 degrees Centigrade (1,800 to 3,100 Fahrenheit). Initially there were concerns that at such temperatures the hydrogen gas would boil away. Calculations have now shown Jupiter-mass objects can easily hold onto their hydrogen gas even at these temperatures.

Although these planets can *survive* in such close orbits, current theory strongly argues that they cannot *form* in such close orbits. Theorists have offered two scenarios to explain the presence of big planets so near their star, both of which require that the planet forms far out in the protostellar disk. One model suggests that gravitational interactions between a planet and a thick protostellar disk will "viscously" pull the planet in toward the star. Once the planet gets very close to the star the orbit can be stabilized by tidal or magnetic forces from the rapidly rotating protostar. Another model suggests that gravitational interactions between planets in systems with multiple Jupiter-like planets will result in one planet being thrown into a close orbit with other planets being thrown to more distant orbits.

The recent discovery of a Jupiter-mass planet in a 40-day orbit suggests that there may not even be a distinct 51 Peg class of planets, but rather planetary orbits may occupy a continuum of distances. Theorists are now reconsidering the possibility that these planets may have formed in these very short-period orbits. Such planets would presumably be enormous rocks and not gas giants like Jupiter.

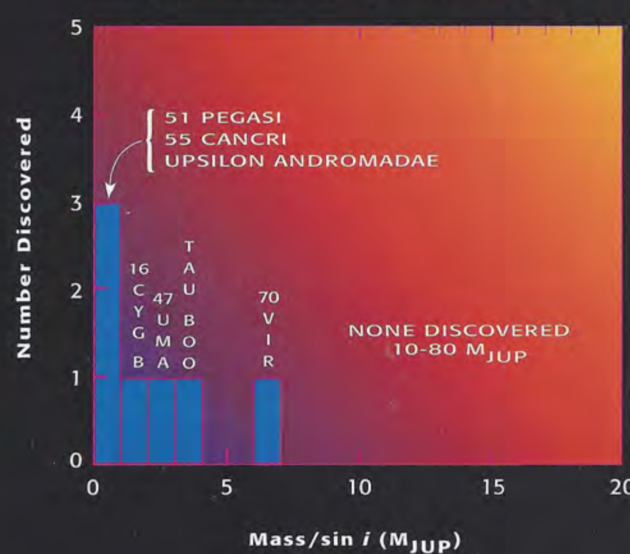
Although theoretically troublesome, 51 Peg-type planets are observationally the easiest to detect. Being very close to their parent stars, these planets exert a much stronger gravitational tug, resulting in a much larger Doppler shift. Moreover, their brief orbital periods allow many orbits to be observed in just a few months. From the Lick survey, it appears that about 3 percent of solar-type stars have these odd companions.

Figure 3: Doppler Velocities of 47 Ursae Majoris



Nine years of data on 47 Ursae Majoris reveal the most solar-system-like planet yet found. This planet orbits its star every three years at twice the distance of Earth from the Sun. The planet has about 2.5 times the mass of Jupiter, and its orbit is circular, like the orbits of the nine planets in our neighborhood in space.

Figure 4: Planetary Mass Function



In this mass-distribution histogram of seven nearby planets, we see a startling absence of objects with mass greater than 10 Jupiters. The gap between 10 and 80 Jupiter masses shows that the extrasolar planets we've detected so far are distinctly different from small-mass stars and brown dwarfs. On the other hand, the increasing number of objects detected at lower masses suggests that even smaller—and more Earth-like—worlds may be more plentiful yet. Improvements in planet-searching capabilities will one day give us the answer.

Charts: Paul Butler; modified by B. S. Smith

Eccentric Planets

The second-largest group found to date is the "eccentric planets." These objects have orbital periods ranging from 3 months to 19 months and mass ranging from 1.7 to 10 times that of Jupiter. Their orbital shape is extremely eccentric (egg shaped), unlike the nearly circular orbits of planets in our solar system. Because the first two eccentric planets,

Above: No one has yet seen a planet around another star—such planets are too faint and too far away to be seen with current technology. We know these worlds only through their effects on their parent stars. Artists can imagine what such a world might look like. This is Dale Darby's view of how the planet around 70 Virginis might look. Painting: Dale Darby

Right: Might extrasolar planets possess the necessary conditions for life? Scientists used to think a habitable planet would have to orbit its star at roughly the same distance Earth orbits the Sun, a region where water would exist on the surface in liquid form. But recent discoveries of Jupiter-like planets orbiting quite close to their stars and of a possible ocean on Jupiter's moon Europa have expanded our ideas about the habitable range. In Sunset on an Ocean Moon, *artist Dan Durda speculates on what a habitable world around another star might look like.* Painting: Dan Durda

70 Virginis and HD 114762, had relatively large mass (7 and 10 Jupiter-masses, respectively), many theorists argued that these objects were brown dwarfs.

In October 1996 it was announced that the Lick team and the University of Texas team of William Cochran and Artie Hatzes had independently found a third eccentric planet (16 Cygni B), this time with a mass only 1.7 times larger than Jupiter. The mass of the planet orbiting 16 Cyg B is so low that it cannot be a brown dwarf, yet it is in the most eccentric orbit found to date. Thus orbital eccentricity cannot be used blindly to discriminate between planets and brown dwarfs. A few potential models have been proposed that explain the non-circular orbits of the eccentric planets, including gravitational interactions between competing Jupiter-mass planets and gravitational interactions between a protostellar disk and the protoplanet.

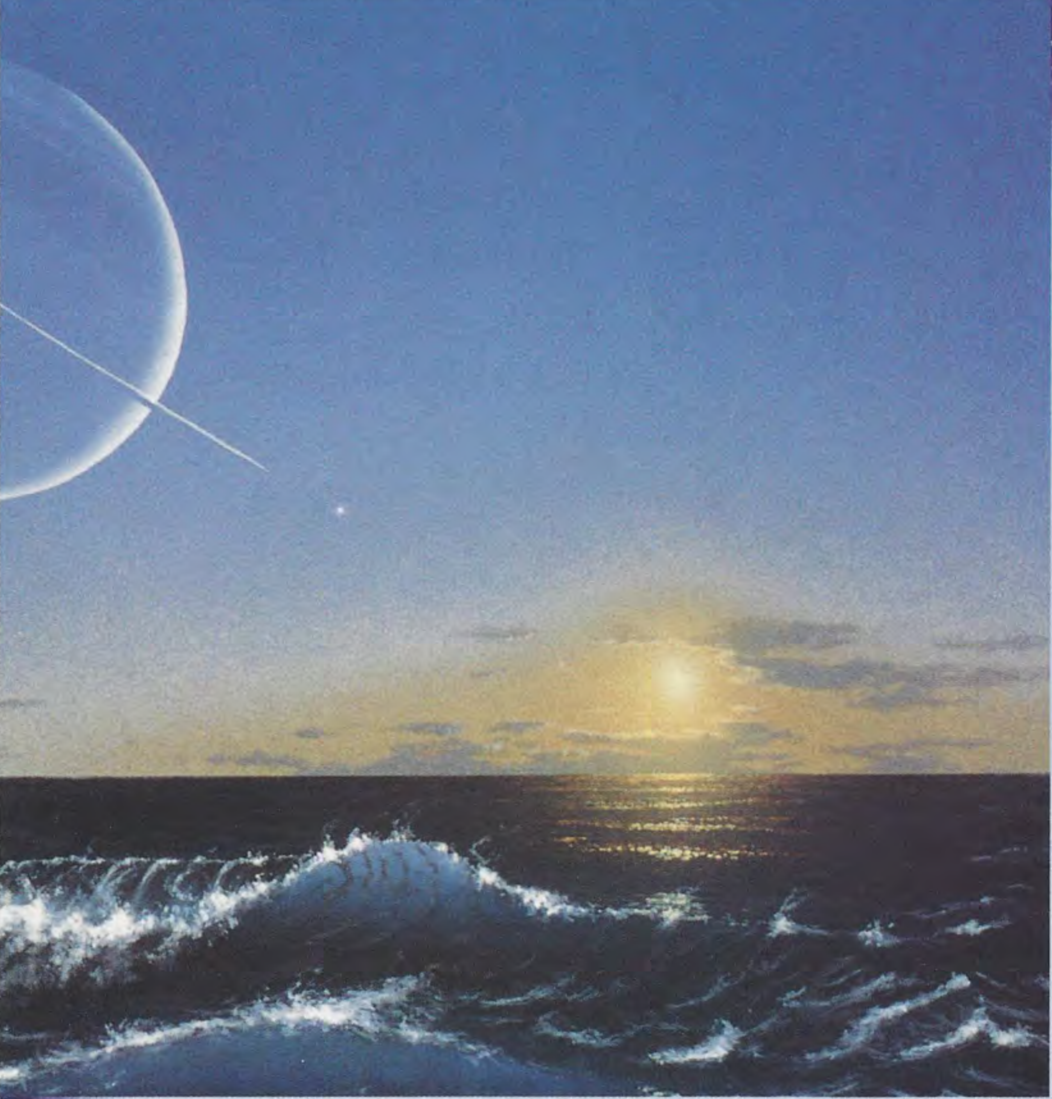
Jupiter-Class Planets

The final group of planets might be called the "Jupiter-type." So far there is only one extrasolar member of this group, orbiting 47 Ursae Majoris (47 UMa). The observed Doppler velocities of 47 UMa, shown in Figure 3 (page 11, top), indicate that the orbital period is three years. The figure also reveals the big improvement in precision that was made in late 1994. The sinusoidal (S-shaped) nature of the velocity variations indicates that the orbit is circular. The mass of the companion is 2.5 times larger than that of Jupiter. If placed in the solar system, such a planet would orbit between Mars and Jupiter, perhaps looking like Jupiter's big brother. The Jupiter-type planets are anthropocentrically the most exciting because they remind us of the solar system.

Figure 4 (page 11, bottom), "Planetary Mass Function," sorts planets detected in precision velocity searches according to their mass, which gives us a way to investigate the relative numbers of high-mass planets and low-mass planets. This diagram strongly suggests that there are more low-mass planets (less than one Jupiter-mass) than high-mass planets (greater than five Jupiter-masses) planets. Given that the current crude state of technology strongly favors detecting high-mass planets and brown dwarfs, it can be assumed that we are only seeing the tip of the "true" planetary mass function and that there are many times more low-mass, even Earth-mass, planets than there are Jupiter-mass planets. The complete lack of objects of more than 10 Jupiter-masses is puzzling because such objects would be the easiest to detect. This again strongly argues that the objects that have been detected so far are not brown dwarfs and that brown dwarfs, at least near solar-type stars, are relatively rare.

The Future of Extrasolar Planet Studies

Several new technologies are being developed to search for planets. Within a few years optical interferometers will probably be capable of astrometrically detecting extrasolar



Key Terms

Astrometry – The precise measurement of stellar positions.

Astronomical Unit (AU) – Average distance between Earth and the Sun. Jupiter orbits the Sun at 5.2 AU.

Brown dwarf – Object that forms like a star but has final mass of less than 80 Jupiter-masses. Objects of more than 80 Jupiter-masses sustain nuclear fusion in their core and are thus stars. Brown dwarfs are usually thought to have a minimum mass greater than about 10 Jupiter-masses.

Protostellar disk – Disk of gas and dust that surrounds young stars. Planets, including those in the solar system, form from this disk material.

planets. Space-based techniques could be ready within twenty years, including next-generation optical interferometers that would be able to image extrasolar planets directly. On a longer time scale NASA Administrator Dan Goldin has proposed building an enormous, one-mile space telescope that would be capable of imaging the mountains and oceans on Earth-like planets around other stars.

In the near term, though, it will be up to the precision Doppler surveys to carry out the first major reconnaissance of extrasolar planets. The Swiss team has recently increased the size of its northern-hemisphere survey from 142 to 300 stars. By the end of 1997 they plan to begin a 400-star survey in the southern hemisphere. With their current precision of 15 meters per second, this group is most sensitive to 51 Peg-type planets and massive eccentric planets.

In July 1996 we began a 300-star survey from the world's largest telescope, the 10-meter Keck, and in October 1997 we will begin a southern-hemisphere survey of 150 stars using the 3.9-meter Anglo-Australian Telescope. Expanding from the original Lick sample, we are surveying 500 stars with a precision of 3 meters per second. This precision will allow us to detect systems similar to the solar system with Jupiter-like and Saturn-like planets.

In late 1998 the University of Texas group plans to begin surveying 400 northern-hemisphere stars using the 9-meter Hobby-Eberly Telescope. By the year 2000 an additional 400 southern-hemisphere stars will be under survey with the Very Large Telescope in Chile.

Within 15 years we will have completed the first reconnaissance of planets orbiting our nearest neighboring stars (within 200 light-years). We will then be able to offer preliminary answers to a number of old questions: What fraction of stars have planets? How many kinds of planetary systems are there? What fraction of planetary systems are similar to the solar system?

Paul Butler is currently an astronomer at San Francisco State University and the University of California, Berkeley. In the fall of 1997 he will join the staff at the Anglo-Australian Observatory in Sydney, Australia.

We encourage interested readers to look at our World Wide Web page, which includes observational data for extrasolar planets, many of our papers, and several useful links: http://cannon.sfsu.edu/~williams/planetsearch/planetsearch.html

Tribute to Clyde Tombaugh

by David H. Levy

The Illinois farm boy who grew up to become a planet hunter poses at the eyepiece of the telescope with which he discovered Pluto in 1930.

Photo: Lowell Observatory, courtesy of New Mexico State University

With the passing of Clyde Tombaugh last January 17, astronomy lost one of its legends, the discoverer of the solar system's outermost planet. For most of this century he was the only astronomer to have discovered a planet.

From his birth on an Illinois farm in 1906 to his death in Las Cruces, New Mexico almost 91 years later, Clyde William Tombaugh was a true lover of the sky who understood what it meant to freeze at the telescope on a cold night, and what it meant to find a new world.

The story of his discovery of Pluto began in 1928, when the young farm boy sent his drawings of Jupiter and Saturn, done from observations through a homemade telescope, to the Lowell Observatory. The response was swift: a job offer at the observatory. When he arrived in Flagstaff during the early months of 1929, he learned that his task would be to search for a possible ninth planet in the solar system. Within a few months Clyde had recast the survey to search areas where a planet so far away would be easiest to spot by the rate of its motion through the sky.

On February 18, 1930, Clyde was scanning a pair of photographic plates he had taken in the constellation Gemini, using a scanning device called a blink comparator. As the machine "blinked" from one plate to an identical shot taken several days later, he noticed a faint object that changed position against the backdrop of stars. "That's it!" he said to himself. Less than a year after beginning his search, Clyde Tombaugh had discovered the solar system's ninth planet.

Pluto was not his only discovery. Other brilliant findings—a supercluster of galaxies between Andromeda and Perseus, five open star clusters and a globular cluster, a cataclysmic variable star in Corvus, hundreds of asteroids, and a comet—made him one of the most productive observational astronomers of the century.

One of Clyde's least-known contributions was not an object but an idea. In the 1930s and 1940s, Edwin Hubble was the reigning galaxy expert, a scientist esteemed as infallible by the public and by many of his colleagues. Hubble believed that space was filled with evenly distributed clusters of galaxies. He based this conclusion on sample areas photographed through the 100-inch Hooker telescope on Mt. Wilson. Clyde thought that the distribution of galaxy clusters was not even. From examining the entire sky through his wide-angle camera, he noted crowded areas where clusters of galaxies were thick and great voids where they were rare. In the 1940s, Clyde met with the great cosmologist and presented his arguments for an uneven distribution of galaxy clusters in space. Hubble ignored him.

Although Clyde wanted to publish his galaxy distribution results, events were to take a different turn. Forced to leave Lowell in 1946, allegedly because of a lack of funding, Clyde started a whole new career at White Sands Proving Ground (now White Sands Missile Range) near Las Cruces. His work on the distribution of galaxies in space was never completed, and it was left for George Abell of UCLA, working at Palomar Observatory, to publish the first major paper challenging Hubble's idea.

Meanwhile, in New Mexico, Clyde began to play a pivotal role in the development of rocket flight. There, his skills as a telescope builder served him as he designed the optical tracking system for V-2 missile launches. Knowing about sun angles and atmospheric seeing, Clyde set the launch schedules for V-2 and later rockets so that his telescopes could record them at optimum times. All the views of rockets in flight with which we are all so familiar, from triumph to tragedy, got their start with the simple telescopes Clyde designed half a century ago.

Around this time, a young army scientist named Brad Smith joined Clyde in his research. The two became lifelong friends. Brad went on to become the first PhD in Clyde's new astronomy program at New Mexico State University (NMSU); later, Brad headed the imaging team for *Voyager 1* and *2*.

Clyde retired in 1973. More than a decade later, NMSU asked him to lead a fundraising effort for the Tombaugh Scholars Program, and for several years Clyde and his wife Patsy crossed the continent, lecturing about his greatest discovery. It was during these lectures that thousands of people got to know Clyde, the man famed as one of the best observers and one of the worst punsters in the history of astronomy.

A favorite: one day at White Sands, the countdown was repeatedly delayed for a balky missile. Recognizing the growing tension of the crews, Clyde grabbed a microphone and called across the range, "If that missile won't work, fire it!"

In 1978 James Christy discovered Charon, Pluto's moon. It was fortunate that just a few years later a rare series of occultations of Pluto and Charon, and an occultation of a star by Pluto, allowed astronomers to determine the diameter of the planet as 2,300 kilometers (1,400 miles). Previously there had been discussion about whether Pluto was large enough to be considered a planet. It turned out Pluto was far larger than the minimum size (about 1,000 kilometers, or 600 miles) for an object to assume the spherical shape characteristic of a planet.

Clyde Tombaugh was one of the last of that breed of astronomers who brave frigid nights in a lonely dome, pointing their telescopes to the night sky and searching. The spirit of Clyde Tombaugh remains an inspiration.

David H. Levy, for many years a leading figure among amateur astronomers, is the co-discoverer of Shoemaker-Levy 9, the headline-making comet that collided with Jupiter in July 1996.

Growing the Planetary Society: New Advisory Council Formed

by John M. Logsdon

Things are changing at the Planetary Society. Carl Sagan's death provided an unwelcome but potentially productive opportunity to rethink the Society's approach to achieving its goals. Bruce Murray's election by the Board of Directors to the presidency of the organization and their choice of Laurel Wilkening as vice president are just the first steps in the process of regeneration.

Another step—with the potential to move the Society forward in many new directions—is the establishment of a new Advisory Council. The directors have asked me to serve as chair of this new group, and I am delighted to accept this appointment and challenge. I believe the council can be a potent force helping shape the Society into a stronger, more effective means for achieving our shared vision of exploring the solar system and searching for extraterrestrial life.

Since its founding in 1980, the Society has had a Board of Advisors, made up of accomplished individuals whose names adorned our stationery and publications. Each member contributed in some way to the Society's growth and development, but the advisors never met as a group. Although they were on tap for individual consultation by the Society's leaders, they did not serve as a source of collective advice or wisdom. Nor did they have the opportunity to develop new ideas arising from their synergetic interaction with other advisors.

With the backing of the Board of Directors, I intend to strengthen the Society by tapping the great potential in the new council. We will work together to bring new ideas and perspectives to the Society and to review the Society's new initiatives. We offer our energy, experience, and—I hope—collective wisdom.

Many members of the old Board of Advisors have asked to stay involved and are now members of the new council. Others have stepped aside so that individuals from diverse backgrounds and experience can add their vitality and commitment to the council's work. We intend to add more members from outside the United States to help make the Planetary Society's voice stronger around the world.

I am looking forward to working with this talented and multi-dimensional group. We will meet at least once a year, and I have scheduled the first meeting for this July during Planetfest '97. There the council members will discuss how we intend to operate as a group, what our charter should be, how we can best relate to the Society's overall membership, and what ideas we have for the future.

The Advisory Council is still in the formative stage. It is intended, among its other purposes, to serve as one channel of communication between the Society's members and its leaders. Thus, as the new council chair, I am very open to your suggestions. My address is Space Policy Institute, George Washington University, Washington, DC 20052. My e-mail address is: logsdon@gwis2.circ.gwu.edu. And my fax is 202-994-1639. Let me hear from you, please.
—*JML*

New Advisory Council Chair

John M. Logsdon

John Logsdon is a self-described "career academic, having taught at the Catholic University from 1966 to 1970 and at George Washington University ever since." He is Professor of Political Science and International Affairs and the founder and director of the university's Space Policy Institute. The institute is a research, graduate education, and professional and public outreach organization focusing on the United States' space program and its cooperative and competitive interactions with space efforts around the world. As John describes his work, "My research goes in two complementary directions: understanding the policy history of space activities and examining policy options for their future. My 31 years working inside the Beltway have made me knowledgeable, but I hope not overly cynical, about how federal policy and politics affect the US space effort." About his qualifications as chair of the new Advisory Council, John says: "I have lots of experience participating in, and often chairing, panels composed of highly qualified and experienced people with strongly held ideas."

New Advisory Council Members

Donna Shirley

In her position as Manager of the Mars Exploration Program at the Jet Propulsion Laboratory, Donna Shirley leads the planning and implementation of NASA's missions to Mars. But to the Planetary Society's directors and staff, Shirley is known as one of our most dedicated and helpful members. She is part of the Society's New Millennium Committee, a group of special donors who are dedicated to ensuring a hopeful future among the planets. With almost 35 years' experience in aerospace and civil engineering, she has served as project engineer for the Comet Rendezvous-Asteroid Flyby/*Cassini* mission and as manager of the *Mars Pathfinder* Microrover Flight Experiment, which produced the microrover *Sojourner*. The rover was named in a Planetary Society contest at her suggestion. She brings space program experience, management savvy, and dedication to the Advisory Council.

Stephen Jay Gould

Author of *The Panda's Thumb, Wonderful Life,* and *Dinosaur in a Haystack*, among other popular books, Stephen Jay Gould may be the world's best-known writer who is also a working scientist. His field is paleontology, once widely thought of as the study of things long-since dead. But Gould finds life interesting, in all its intricate and often strange forms, and so his books are about how things live and evolve. On our Advisory Council, he will be a unique resource—the more so as scientists come closer to finding answers about the possibility of life on ancient Mars. Gould is Professor of Geology and Alexander Agassiz Professor of Zoology at Harvard University, where he also serves as curator for invertebrate paleontology of the Museum of Comparative Zoology. Throughout his career Gould has been a prolific contributor to scientific journals. His latest popular work is *Full House: The Spread of Excellence from Plato to Darwin.*

Basics of Spaceflight: Deep Space Network, Continued

by Dave Doody

In the 1950s the Army contracted with Caltech's Jet Propulsion Laboratory (JPL) to create and launch the first US satellite, *Explorer 1*. To receive telemetry from the satellite as well as track it and plot its orbit, JPL deployed three portable tracking stations around the world. Later, transferring from the Army to the newly created NASA, JPL took on responsibility for the design and operation of various automated lunar and planetary exploration programs. The initial network of tracking stations grew along with the US space exploration program, eventually becoming today's worldwide, multi-faceted Deep Space Network (DSN).

The DSN's antennas, called Deep Space Stations (DSSs), evolved to meet the increasing needs of flight projects. DSS-12 at Goldstone, California, for example, had a main reflector 26 meters in diameter when it was built in 1961. In 1979, it was increased to 34 meters in diameter, and so were its counterparts in Spain (DSS-61) and Australia (DSS-42). In 1966 we added the giant 64-meter DSS-14 at Goldstone, which was extended in 1988 to 70 meters, the better to receive *Voyager*'s signals from distant Neptune. The same changes were made at the Spanish DSS-63 and Australian DSS-43. There have been many improvements and new DSSs added to support an increasing number of interplanetary flight projects.

Arrays: Bigger Than the Biggest Dish

Of course, the bigger the collecting surface of an antenna, the better it can concentrate a spacecraft's signal while rejecting noise. And the better this ratio of signal to noise, the more data a spacecraft can send per second (and it's very desirable to achieve the highest rates possible). But the 70-meter DSSs are probably the largest steerable antenna structures that will ever be built in the DSN. Anything larger would be prohibitively expensive and too large and heavy to attain the extremely high precision we need. Fortunately, there's a trick we can employ to increase collecting area, thereby increasing the signal to noise ratio, so spacecraft can send their data at faster rates. The trick is called "arraying."

If you point two or more DSSs at a spacecraft, you can electronically combine the signals they collect just as though you were using a single, much larger antenna, but without the mechanical nightmare of a huge structure. It's a very intricate technique. For one thing, the radio signals from all the arrayed antennas have to be kept in phase (that is, in step). If you keep them in phase, the signals "add" and become stronger. But let them slip out of phase and they can cancel each other out. The process isn't perfect, of course; there are inefficiencies: it takes four 34-meter antennas in an array to match the collecting ability of one 70-meter antenna. Nevertheless arraying has become a very useful method for capturing signals from *Galileo*, *Voyager*, and other distant spacecraft. It's even routinely possible to combine antennas on different continents into a single array!

Interferometry Buys a Sharper Image

There's another technique, pioneered with the DSN, that uses multiple antennas. Interferometry uses two or more antennas to increase resolution instead of increasing signal strength. The name comes from the science of how waves from different sources "interfere" with each other when they're lined up just right.

What are the benefits of increasing resolution? Look at Saturn with a small telescope, having an aperture (the size of its mirror or lens) of one inch. Then look at the same planet through a larger telescope, with an aperture of eight inches. Generally, you'll have much better resolution, seeing the rings more clearly, with more detail visible. Now suppose you could increase your telescope's aperture from eight inches to 8,000 miles. The resolution would certainly improve!

Interferometry isn't practical yet with visible-light imaging (give it 10 or 20 years), but it can be done today with radio waves, since they're longer and easier to handle than light. By using DSN antennas, or other radio telescopes separated by thousands of miles, you can achieve the same resolution as if you had a single antenna thousands of miles wide. The result is that spacecraft navigators can pinpoint their vehicles with extreme precision and astronomers can obtain radio images of celestial objects with high resolution. Remember, resolution is the idea here; with interferometry you don't get the signal strength of an aperture thousands of miles wide, just its resolving power.

Since the baseline, or distance between the antennas, is very long, the technique is called Very Long Baseline Interferometry, or VLBI (see Basics of Space Flight in the July/August 1995 *Planetary Report*). In theory, there's no limit to how large an aperture you can synthesize with VLBI. If we had a radio telescope on the Moon paired with one on Earth, it would provide the resolution of an antenna 250,000 miles wide. While that's not yet a reality, the DSN is gearing up to play a major role in Space VLBI—a radio astronomy project that will soon combine orbiting spacecraft with ground antennas to provide longer baselines than are possible on Earth's surface. This international project teams the DSN with spacecraft built by Japan and Russia.

VLBI can also be applied upside down. That is, instead of

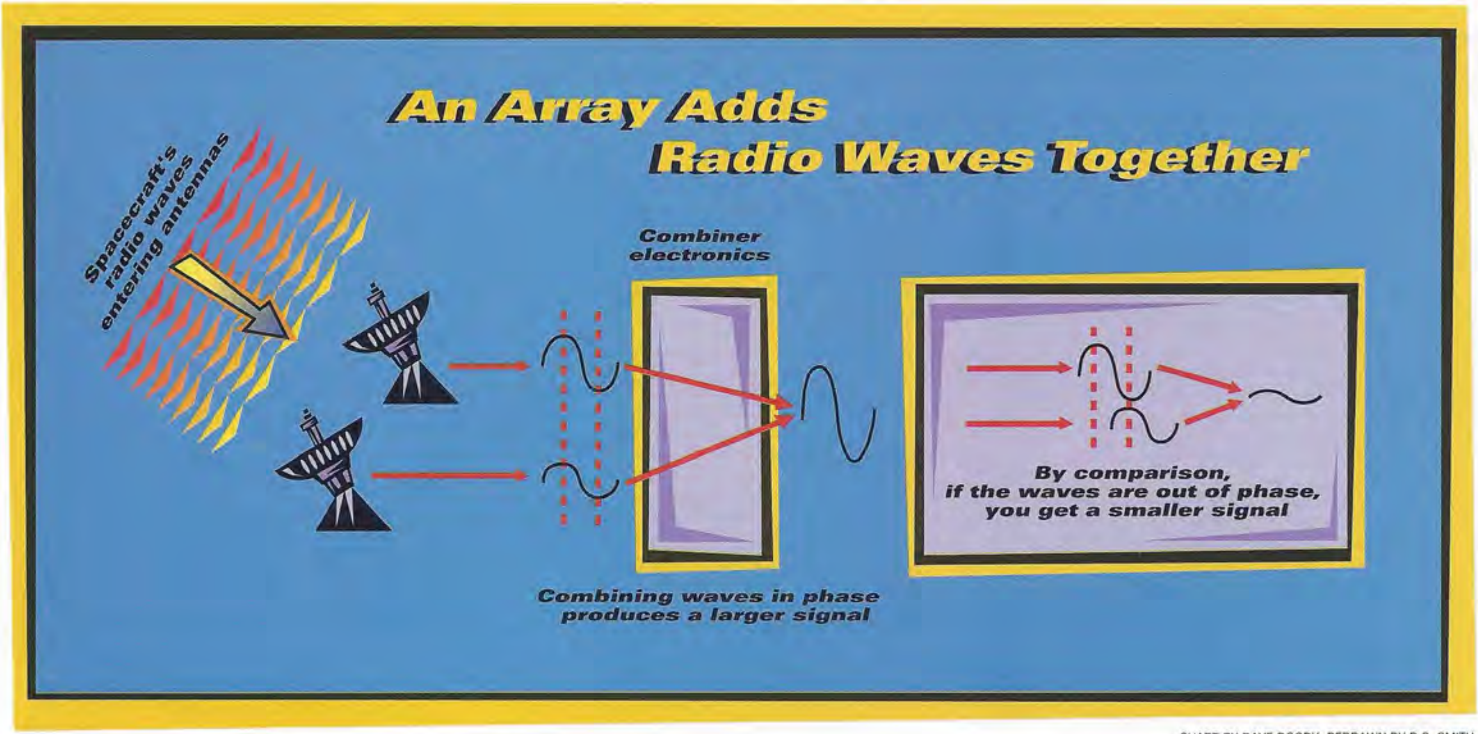


CHART BY DAVE DOODY; REDRAWN BY B.S. SMITH

using the technique to map a celestial object with high resolution, you can map the antennas' locations with resolution down to a fraction of a centimeter. By this means, you can measure how far Earth's continents drift as the years go by, driven by our planet's plate tectonics.

Radio astronomers use the DSN antennas, either singly or in combination, for a wide variety of observations that complement the use of other radio astronomical observatories around the world, examining galactic nuclei, black holes, supernovae, interstellar clouds and chemistry, star formation, stellar emission mechanisms, stellar envelopes, and more. Scientists in a range of disciplines, from physics to geology, make excellent use of the DSN in its "spare time" between spacecraft-tracking jobs.

More Hats for the DSN to Wear

As if it weren't enough to track interplanetary spacecraft with single antennas and arrays, measure continental drift, and carry out radio astronomy observations with single antennas and with VLBI, the DSN has a few more extraordinary roles. The NASA search for extraterrestrial intelligence (SETI) employed the 70-meter DSS at Goldstone for a time. Even though SETI isn't done with the DSN any more, following cancellation of the program by Congress in 1991, the signal-searching technology that started out using DSN resources lives on today in surveys being conducted by the Planetary Society (see Basics of Space Flight in the March/April 1996 *Planetary Report).*

Astronomers specializing in planetary radar astronomy use the large dish at Goldstone (DSS-14) to send rather than receive radio signals, transmitting a very powerful microwave beam to "illuminate" distant objects in the solar system. The signal reflected from the target returns to Earth to be gathered by the DSN antennas or by other radio telescopes such as the National Radio Astronomy Observatory's Very Large Array in New Mexico. As part of the Goldstone Solar System Radar (GSSR) program, radar astronomers have pointed this powerful active radio sensor toward all our neighboring planets to study them, as well as toward asteroids that pass close to Earth, such as Toutatis. Radar astronomers have detected features on the planet Mercury that appear as strange, reflective polar caps, quite likely made of water ice hiding from the Sun behind crater walls. Saturn's moon Titan shows features that may be oceans of ethane and solid continents.

Aside from taking the active role in radar astronomy, the DSN can be used as a passive instrument with a technique called bistatic radar (in this context, bistatic means "two stations"). A spacecraft near a distant planet supplies the illuminating beam of radio "light," pointing it down at its planet at just the correct angle so it will glance off and be received by the DSN. Once received, the signals can be examined to tell a lot about the illuminated object. *Magellan* used this technique a few times to scrutinize some small patches on the surface of Venus. *Clementine* did the same thing with the Moon, and the results there seemed to reveal pockets of water ice in shaded polar craters.

DSN's future will surely include new and continually improving capabilities to support new spacecraft and other scientific endeavors. Also, its level of automation will continue to increase, making it easier and less costly for customers to use. Last year, by the way, the DSN retired good old DSS-12 from service, transferring it to the Apple Valley Science and Technology Center. Now known as the Goldstone Apple Valley Radio Telescope, it will serve many years as an educational resource for students throughout the country.

If you have access to the Internet, be sure to see the DSN's site (http://deepspace1.jpl.nasa.gov/dsn) for more information and pictures.

Dave Doody is a member of the Jet Propulsion Laboratory's Advanced Mission Operations Section and is currently working on the Cassini *mission to Saturn.*

JPL's *Basics of Space Flight* manual is online at
http://www.jpl.nasa.gov/basics/

News and Reviews

by Clark R. Chapman

The planet Venus is a mirror in which David Grinspoon reflects on his life, on the universe, and on everything in between. Don't be fooled by his new book's title, *Venus Revealed* (Addison Wesley, 1997, 355 pages, $27.50), into thinking that the volume is just about a single rather hellish planet. This tour of modern planetary science refers to Venus only a bit more often than to other worlds.

Grinspoon, a University of Colorado assistant professor, is the closest thing we have to a Hunter Thompson in planetary science. (Thompson is the writer whose highly personalized style gave us the term "gonzo journalism.") Grinspoon offers us his view of the universe as personal musings about Venus, beginning at the dawn of civilization, when the comings and goings of the Evening Star imbued it with great religious significance, and proceeding up to the *Magellan* mission's thorough geological investigations of Earth's erstwhile planetary twin. Rock music lyrics and other cultural metaphors pervade the book.

Grinspoon eschews the traditional "Great Man" or even "Esteemed Colleague" approach to reporting progress in the planetary sciences. For Grinspoon, modern planetary research is a collective, cultural enterprise. We accompany him on a journey of awakening consciousness, from a memory of watching Neil Armstrong's "first step" to a mature evaluation of *Magellan*'s radar maps of Venus. The book's index lists many people, such as C. S. Lewis, John Lennon, and Dr. Seuss, but you look in vain for Carl Sagan, Jim Head, or even *Magellan* project scientist Steve Saunders.

A Dreaded Chapter

I cringed as I began reading the final, 50-page chapter entitled "Life on Venus." But I should not have worried. It is a wonderful philosophical ramble about life in the universe, written by a dabbler in biology, with thankfully few references to Venus as a potential habitat. After all, Venus is the epitome of the inhospitable planet, and even were silicon-based organisms to exist, there is little to be said about them—not enough to fill even a fraction of 50 pages. Fortunately, halfway through the chapter Grinspoon moves beyond its title topic to discuss future robotic exploration (and terraforming) of Venus and other planets.

A wonderful thing about *Venus Revealed* is that it is the opposite of an authoritative text on "what we know." Science for Grinspoon is a process of discovery that involves a constant testing of our assumptions and constant attempts to transcend our Earth-oriented prejudices to see new worlds for what they are in their own right. Grinspoon accurately describes much of the modern thinking in planetary science (for example, about how planets form and how their atmospheres evolve), but he reminds us of where our logic may be leading us astray and of how little we truly know for sure.

The following sentences exemplify the author's *weltanschauung:* "How do we know that we are observing the solar system at a 'normal' time? that our system of planets is 'normal' at all? or even that our part of the universe or our particular epoch—the time we happen to have come along to briefly observe things—are at all typical of the wider and longer-lived universe?"

Footnotes With Flavor

While the volume is clearly intended for the "intelligent layman," who will only rarely encounter unintentional jargon, planetary researchers should enjoy the book's philosophical threads as well. Of course for them a session reading *Venus Revealed* will lack the thrills of recognizing the acknowledged involvements of oneself or one's colleagues that are part of the fun for a scientist when reading a traditional book that discusses the accomplishments of individual researchers.

Grinspoon's writing is self-conscious but excellent, even though he lacks the restraint to omit an occasional nerdy in-joke. (The latter two traits are illustrated when he introduces the concept of Avogadro's number by way of an anecdote about his typing speed.) I enjoyed the odd little footnotes that were sometimes helpful, usually amusing, and occasionally bizarre. Indeed, you can capture the book's flavor, but not its substance, by reading just the footnotes one after another, which took me 24 minutes. Another way to preview the book is on the World Wide Web at http://sunra.colorado.edu/david.

Separate essays embedded in the text were more often delightful tangents than the fine-print tutorials for the serious student that I feared they might be. Carter Emmart's unique drawings embellish the text, though an early one messes up the depiction of the phases of Venus rather badly.

Venus hasn't been quite the hot topic it was when *Magellan* was still in orbit, especially given the excitement of *Galileo*'s new pictures of Jupiter, Hale-Bopp in the evening skies, and possible fossil life on Mars. Grinspoon's book is a wonderful vehicle for getting us thinking about Venus again, written after more than adequate time to ponder the lessons learned from the spacecraft missions of exploration.

Clark R. Chapman and his wife Lynda have now moved into their new ranch southwest of Boulder, Colorado, where the nighttime skies are wonderfully dark.

World 
Watch

by Louis D. Friedman

Paris—Some good news for the beleaguered space science community in Europe: the European Space Agency (ESA) has approved a reflight of the four *Cluster* satellites designed to measure Earth's magnetosphere. The original *Cluster* was lost on the maiden flight of the Ariane 5 rocket, which exploded upon launch in June 1996. The reflight, tentatively scheduled for the year 2000, will use the *Soyuz* missions' launch vehicle in a joint venture between Arianespace and the Russian Space Agency. The cooperative launch will save funds that ESA can then put into instruments for the satellites.

Moscow—Failure by the Russian government to fund the Russian Space Agency's share in development of the international space station will delay completion of the first hardware until mid-1998. This is a serious blow to NASA, whose plans and development were proceeding on track. The agency is taking considerable political heat in Washington as a result of this delay.

The situation is important enough to have reached the attention of Russian President Boris Yeltsin, who in mid-April announced that he personally would guarantee proper funding so that Russia could meet its commitments in the international program. This was the highest level of assurance ever stated in Russia for the space station program.

An independent group led by General Thomas Stafford, former *Apollo-Soyuz* astronaut, conducted a fact-finding mission in Russia in the early spring for NASA. They concluded that the Russians should be able to meet their overall space station commitments and that the engineering work on the project is sound. This group's endorsement of the American-Russian arrangements helped forestall a possible challenge in Congress. Nonetheless, Russian failure to meet deadlines and funding commitments threatens the overall project and current approach.

In another major element of U.S.-Russian space cooperation, the Russian Space Agency still officially supports a Mars 2001 joint mission with a Marsokhod rover to initiate Mars Together. However, funding is not yet secured. NASA has said it needs a definitive Russian statement about the Mars 2001 mission by early fall 1997 if Mars Together is to go forward.

Pasadena—The *Galileo* spacecraft continues to perform superbly as it orbits Jupiter and encounters the major satellites. Stunning pictures of Europa and Ganymede have dominated the news—especially those hinting of an ocean below the ice-crusted surface of Europa. Scientists say they might see evidence of liquid water, if *Galileo* can view Europa at different times and at different angles, and possibly even evidence of geysers or ice movement.

They will get the chance. A *Galileo-Europa* mission (GEM) will extend the basic *Galileo* mission beyond the original December 7, 1997 end date. At that time *Galileo* will perform repeated flybys of Europa in an ever-shrinking orbit, providing the variety of views scientists asked for. At the conclusion of GEM, the spacecraft will target Io for one or two close passes until the onboard electronics give out in the intense radiation field of Jupiter.

Funding for GEM was part of the general good news given to NASA's space science program in the administration's Fiscal Year 1998 budget request. Additional funds proposed for *Mars Surveyor* will allow NASA to send orbiter and lander missions at every Mars launch opportunity and, at the same time, prepare for a Mars sample return in 2005. The question of past life on Mars, which made headlines in August 1996 as NASA scientists announced results from studies of an Antarctic meteorite, contributed to the support for this extra funding.

The budget includes the Origins program, a broad space-science inquiry into life in the universe and habitability of other worlds. The search for planets around other stars remains an important component of this program, as do the comparative planetology and astrobiology studies initiated to connect questions of life, habitability, and planetary processes in our solar system—and perhaps in others.

The Planetary Society testified before Congress in strong support of the administration's space-science budget proposals while, at the same time, urging lawmakers to stop the downward trend that continues in overall budget requests for NASA. All four of the congressional space committees asked to hear from the Society, and we submitted statements to them and to the entire Congress as part of our support.

The Society's statement concluded, "By exploring space we become possessed with an idea which brings hope to our nation. We must invest in science and engineering to maintain leadership. And this means fully funding NASA and its missions to uncover the mysteries of our solar system and the universe."

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

Questions and Answers

What makes people think that Comet Hale-Bopp passed Earth before? Couldn't it have originated in the Oort Cloud and for some unknown reason been deflected in our direction?
—João Matos,
Setubal, Portugal

Comet Hale-Bopp probably was indeed a resident of the Oort Cloud for billions of years before passing stars perturbed its orbit to bring it close to the Sun, but its current orbit indicates that it has passed this way at least a few times before.

Astronomers believe that Hale-Bopp made its previous passage through the inner solar system about 4,200 years ago. This figure is based not on historical records of observations of the comet but rather on our precise knowledge of its orbital trajectory. Since shortly after Hale-Bopp was discovered in July 1995, astronomers have been measuring its position relative to the star background and using these measurements to compute the comet's trajectory. The accuracy of the orbital solution for Hale-Bopp has increased as more measurements have been made, and now with over 2,100 measurements in hand, the comet's path is known quite precisely.

Hale-Bopp's motion can be traced backwards in a computer by accounting for all the forces that act on the nucleus at any given time. The strongest of these are the gravitational attractions of the Sun and planets, which are calculated using Newton's law of gravitation. (A more subtle force affecting the motion of many comets is the rocketlike thrust of the comet's jets, but this has little effect on the motion of a massive comet like Hale-Bopp.)

This photo of Hale-Bopp was taken near midnight on March 28, 1997 from the cemetery of the Holy Transfiguration Church in Kenai, Alaska. The Andromeda galaxy can be seen between the church's two right hand crosses.
Photo: Bill Hutchinson

The precision of backwards orbital calculations was demonstrated by the fortuitous discovery of an image of Hale-Bopp taken over two years before the comet was discovered. The position predicted by mathematically tracing the comet's orbit backwards to the time of the pre-discovery image was within 2 arcseconds of the actual position. Following the motion farther back in time, we find that the comet's aphelion (point farthest from the Sun) distance was only about 500 astronomical units (AU). An astronomical unit is the mean distance of Earth from the Sun, about 150 million kilometers (93 million miles). Comets from the Oort Cloud making their first visits to the inner solar system typically come from distances of over 10,000 AU. During each passage through the planetary region, the gravitational influence of the planets, especially that of Jupiter, alters the comet's orbit, often lowering the aphelion and shortening the orbital period. Hale-Bopp's rather small aphelion distance of 500 AU indicates that it has probably passed through the planetary region at least a few times before, its aphelion lowered on each visit. Comet Hale-Bopp's current passage through the inner solar system continues the trend: gravitational perturbations, principally due to Jupiter, have lowered the comet's next aphelion to about 350 AU and shortened its orbital period. Hale-Bopp's next visit to the inner solar system is calculated to occur in about 2,380 years.
—PAUL CHODAS,
Jet Propulsion Laboratory

Due to ejecta from ancient impacts on Mars and its moons, is there a possible rock hazard for spacecraft in Mars' space?
—George Howard,
Kansas City, Missouri

We have suspected, since a 1971 study by Steve Soter, that the near environs of Mars would be populated by debris generated by meteoroid impact. You are correct in thinking that the main source of this debris is not the planet itself but rather its tiny moons Phobos and Deimos. This is because any material ejected from Mars itself with sufficient energy to escape the planet would most probably escape the entire Mars system—just as the famous ALH84001 is believed to have done. However, Phobos and Deimos have very low escape velocities, so most of the escaping material remains bound by the planet's gravity, forming a ring of debris. The primary application of Soter's "moon erosion-dust belt" idea for over 15 years was in development of theories for generating the faint, dusty rings around Jupiter, Uranus, and Neptune discovered by *Voyager*. But in 1989, the short-lived Soviet *Phobos* orbiter discovered possible evidence of material in the orbit of Phobos that stimulated a renewal of interest in Mars' "dust rings." In addition, the Japanese *Planet-B* mission will carry a dust detector.

The size and abundance of any steady-state debris population results from a balance between injection (by meteoroid impact) and removal. Laboratory studies show that most meteorite ejecta velocities are between 1 and 100 meters per second, much smaller than the local orbit velocities of 1.5 to 2.5 kilometers (0.9 to 1.6 miles) per second; thus, the ejecta take up orbits which are fairly circular, not enormously elliptic. Ejecta particles are acted on by solar radiation pressure, gas drag, and electromagnetic forces (after they become charged). The tiniest grains are quickly swept away by the solar wind; the largest particles retain their nearly circular orbits closest to those of their parents. They thus reimpact those parent moons, resulting in their fairly quick removal.

The most abundant grains are in the 10 to 50 micron range (a micron is one millionth of a meter); these have fairly eccentric, loopy orbits that spread over a large area with low probability of reencountering either the parent moons or Mars and are produced in the greatest abundance by interplanetary projectiles. Grains of this size pose little danger to spacecraft. Larger projectiles are required to produce bigger (that is, hazardous) ejecta, but large impacts appear to be too rare to maintain a hazardous abundance of particles in view of the quick removal of large rocks by recollision.

Perhaps of even greater interest, but still somewhat controversial, is the possibility that the material in the orbit of Phobos is primarily gaseous—derived by slow degassing of a volatile component from the satellite. This might support some scientists' long-held suspicion, based in part on its dark color, that Phobos is a "primitive" planetesimal, similar perhaps to comets.
—JEFF CUZZI,
NASA Ames Research Center

How is it that, despite all of the probes and fly-bys of Mars to date, we still haven't quantified Mars' magnetic field? Have we simply not sent the proper instruments yet to make the measurements? Is that why Japan's* Planet-B *mission will be the first to fill in the details? Or is its on-orbit longevity the key?
—Robert C. Gorby,
Camarillo, California

A Soviet orbiter determined an upper limit to the magnetic field of Mars, showing it to be very small relative to that of Earth. More sensitive and comprehensive measurements such as those of *Planet-B* are needed to get a real understanding of Mars' magnetic character. Orbit longevity is a factor. But high magnetometer sensitivity and a magnetically clean spacecraft, in addition to complete geometric coverage, are needed because the Martian field is so weak.

We have, from *Voyager*, magnetic field values for Jupiter, Saturn, Uranus, and Neptune. "Explanations" for any stellar or planetary field are another matter! Scientists generally agree that an internal dynamo, with moving fluids carrying electric currents and magnetism, is the source of the observed external fields, but the picture is complicated by interactions in surrounding plasma, not to mention the difficulty of modeling just what is going on inside a star or planet.
—JAMES D. BURKE,
Technical Editor

Factinos

Comet Hale-Bopp has surprised scientists by sprouting a type of tail never before detected in a comet. European researchers made this discovery in mid-April while using the Isaac Newton Group of Telescopes at La Palma in the Canary Islands. A team from the Padova Astronomical Observatory in Italy; Queen's University in Belfast, Northern Ireland; and La Palma Telescope group found the new tail while they were analyzing the light from the comet.

Spectroscopic instruments were set to exclude all light from the comet except the yellow light emitted by sodium. To the scientists' surprise, this produced the electronic image of a third cometary tail—one made of sodium atoms.

Hale-Bopp's sodium tail, which is very narrow and not visible to the naked eye, is near the ion tail but slightly separated from it. The tail's discoverers calculate that it is about 600,300 kilometers (373,000 miles) wide and about 50 million kilometers (31 million miles) long.
—from Malcolm W. Browne
in *The New York Times*

In February, scientists who drilled core samples from the ocean bed announced that they've found proof that a huge asteroid smashed into Earth about 65 million years ago and probably killed off the dinosaurs. "We've got the smoking gun," said Richard D. Norris, leader of an international expedition that probed the Atlantic Ocean floor in search of asteroid evidence. "It is proof positive of the impact."

Norris' team recovered three drill samples with the unmistakable signature of an asteroid impact. The drill cores include a thin brownish section that the scientists called the "fireball layer" because it is believed to contain bits of the asteroid itself. "These neat layers of sediment bracketing the impact have never been found in the sea before," Norris said. The team drilled below sediments laid down at the time of the dinosaur extinction.

Norris said the deepest layers contain fossil remains of many animals and came from a healthy, "happy-go-lucky ocean" just before the impact. Just above that is a layer of green glass pebbles, thought to be ocean-bottom material instantly melted by the huge energy release of the collision. Next up is a rusty brown layer that Norris believes to be from the "vaporized remains of the asteroid itself."

Just above the brown layer are two inches of gray clay bearing strong evidence of a nearly dead world. This dead zone lasted about 5,000 years, Norris said, after which the core samples show evidence of renewed life. "It is amazing how quickly the new species reappeared," he noted.
—from the Associated Press

Society News

Washington Volunteers Reach Congress

Thanks to our Washington, DC volunteers, the Planetary Society was able to hand-deliver a declaration of support for NASA to all members of Congress, in addition to our targeted campaign that went to the House and Senate subcommittees concerned with NASA budgets for Fiscal Year 1998. Entitled *Mariners in the Sky,* the statement urged legislators to support space science and planetary exploration.

Society members in the Washington, DC area, under the direction of Dr. William Roth of Wheaton, Maryland, prepared this special "mailing," which included copies of the January/February issue of the *Planetary Report*, dedicated to the possibility of past Mars life, as well as the Society's statement regarding NASA budget cuts. Volunteers delivered the packets directly to the Capitol, saving time and money as well as giving the delivery a personal touch.

This effective Washington-area volunteer group is extremely valuable to the Society. We thank Dr. Roth, Danny Pourkesali, and all the volunteers who made this effort a success.
—Louis D. Friedman, Executive Director

New President and Vice President Elected

The Planetary Society's Board of Directors elected new officers during a special meeting in the Washington, DC area in March. Bruce Murray, professor of planetary science at the California Institute of Technology and a founding member of the Society, was elected president, and Laurel Wilkening, chancellor of the University of California at Irvine, was elected vice president.

This board meeting was the first attended by new Society directors Anne Druyan, Donald J. Kutyna, and Kathryn D. Sullivan. Their added energy and wisdom will help ensure that the Planetary Society maintains its momentum as we approach the new millennium.
—Charlene M. Anderson, Director of Publications

New Millennium Video Released

Members of the Society's New Millennium Committee made possible the production of a pilot videotape, *The Last Thousand Days of the Last Thousand Years*, which will be distributed to documentary producers and others in the media to generate interest in the Planetary Society's vision of the future as we approach the twenty-first century. Based on an original concept by New Millennium Committee member Polly Brooks, written and directed by Jon Lomberg, and narrated by Majel Barrett-Roddenberry, the video focuses on the advancement of the sciences over the last thousand years and looks to the next thousand, an era of wonders in store for humankind.

The 12-minute videotape is available to members who would like a copy. Send $5 for shipping and handling to: New Millennium Video, The Planetary Society, 65 N. Catalina Avenue, Pasadena, CA 91106.
—Carlos Populus, Volunteer Coordinator

New Donations

We gratefully acknowledge some important donations to the Society's projects, including a very generous anonymous donation from a New Millennium Committee member. The New Millennium Committee has now grown to more than 250 members and accounts for a significant percentage of Society donations.

Warner Brothers donated $25,000 in memory of Carl Sagan, with whom they were working on the motion picture version of his book, *CONTACT*, which is set to be released this July. Dr. George Friedman (no relation to our executive director), research manager of the Space Studies Institute, contributed $1,000 for the second time to our Near Earth Object (NEO) Observation fund. NEO discoveries are a common interest for both organizations. *—LDF*

Annual Audit Completed

The firm of Martin Werbelow and Company has completed its yearly audit of the Planetary Society. The firm determined that the Society's 1996 financial statement was in conformity with generally accepted accounting principles.

Copies of the financial statement are available upon request.
—Lu Coffing, Financial Manager

Mark Your Calendar

• *January 1998 Crater Trekking in Belize*. Join in the Society's series of searches for evidence of the Cretaceous/Tertiary impact that caused the extinction of the dinosaurs. Contact Lu Coffing at Society headquarters.
• *February 26, 1998 Caribbean Solar Eclipse Cruise*. Set sail to observe this spectacular event. Contact Susan Lendroth at Society headquarters.

More News

Mars Underground News:
NASA rethinks missions to Mars for 2001 and beyond; *Pathfinder*'s historic descent and landing on Mars.
Bioastronomy News:
Oceans on Europa; evaluating public interest in life in the universe.
The NEO News:
The role of the amateur astronomer is changing with new technologies, grants, and programs.

For more information on the Society's special interest newsletters, phone (818) 793-5100.

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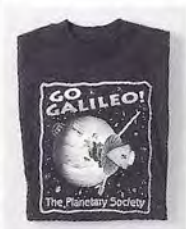

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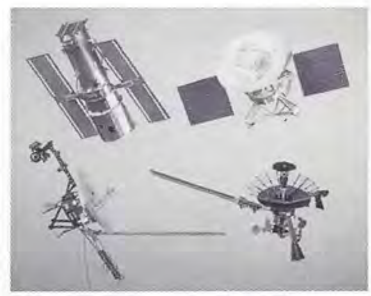

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#337 Uranus
#340 Venus

Paul Cézanne once wrote, "You have to look at nature as if no one had ever seen it before." In *Surfaces, #116*, Jacques Garnier shows his appreciation for objects massaged, and often ravaged, by the forces of time and nature. In this photograph he portrays nature's transforming effect on surfaces through impacts, erosion, and oxidation.

Jacques Garnier is a photographer whose work combines perception of the unseen and overlooked with a philosophy of glorifying the used, worn, and discarded. He lives in Laguna Beach, California.

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