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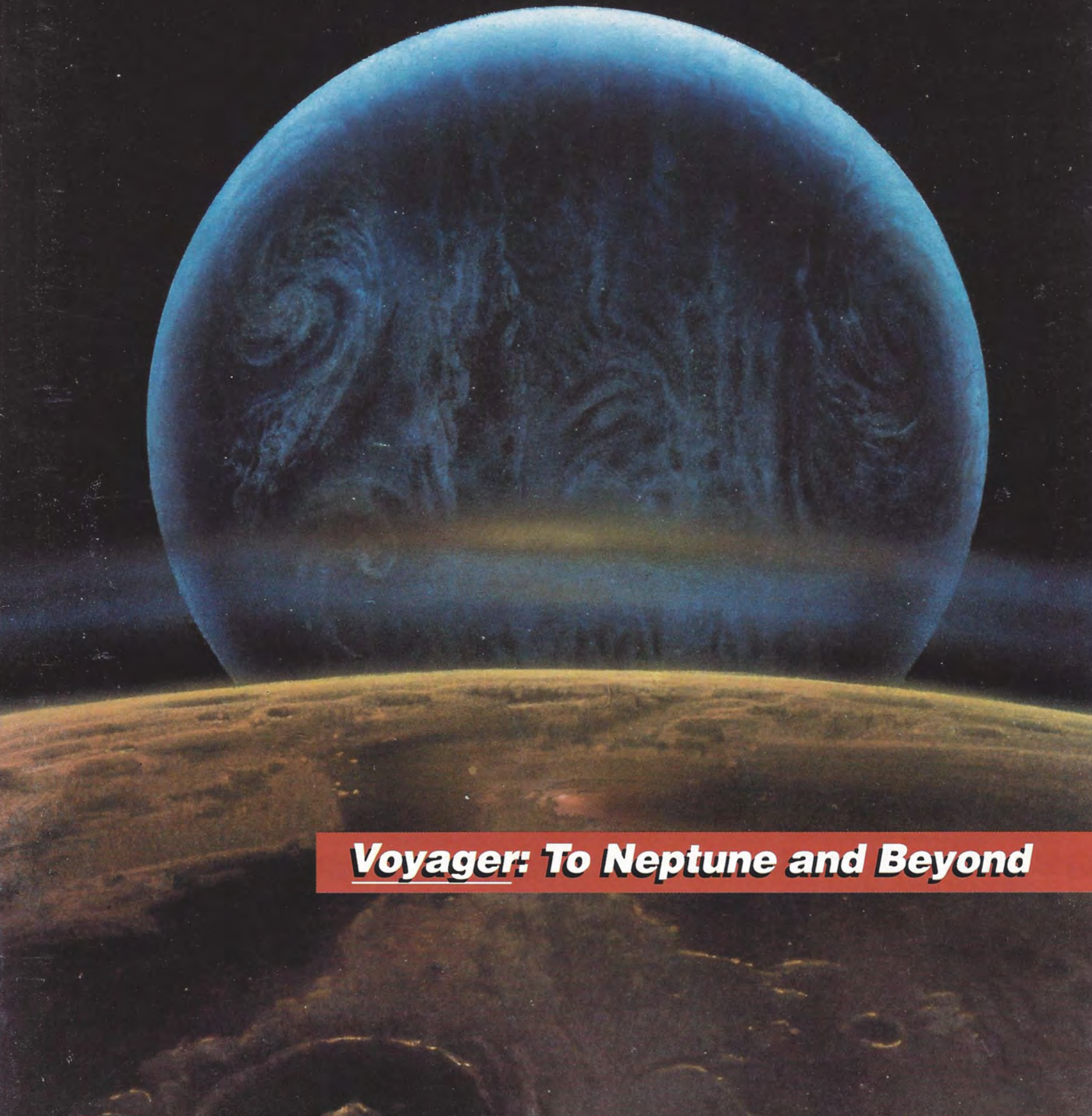

Voyager: To Neptune and Beyond

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Editor, CHARLENE M. ANDERSON;
Technical Editor, JAMES D. BURKE;
Guest Technical Editor, ELLIS D.MINER;
Assistant Editor, DONNA STEVENS;
Copy Editor, KARL STULL;
Art Director, BARBARA SMITH

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COVER: The blue planet Neptune and its tantalizing moon Triton are the last scheduled destinations on* Voyager 2*'s Grand Tour of the outer solar system. Jupiter, Saturn and Uranus have all given up secrets to this robotic emissary from Earth, and the spacecraft will now probe the secrets of its last planet. After swinging past Triton and examining its atmosphere,* Voyager 2 *will begin a quest to find the edge of our solar system, and then will travel on forever through the realm of the stars.

Painting: Paul Hudson, reprinted with permission, © National Geographic Society

VOYAGER: OPENING THE SOLAR SYSTEM

BY CARL SAGAN

In this issue of *The Planetary Report* we celebrate the epic journey of the *Voyager 1* and *Voyager 2* spacecraft and look forward with keen anticipation to the *Voyager 2* encounter with the Neptune system on August 25, 1989. Launched in August and September 1977, the two spacecraft were programmed only to explore the Jupiter and Saturn systems, but they have far exceeded that original mission specification. *Voyager 1*'s trajectory to Titan precluded its visit to any other worlds. But *Voyager 2*, after gravity assists by Jupiter and Saturn, became in 1986 the first artifact of the human species to reach the Uranus system, and this August will play the same role in the Neptune system.

The spacecraft have provided our first detailed, close-up information about dozens of new worlds—some of them previously known only as fuzzy disks in the eyepiece of ground-based telescopes, some merely as points of light, and many entirely undiscovered before *Voyager* approached. One of these moons, Miranda of Uranus, was discovered not only in my lifetime but by my thesis adviser, Gerard Kuiper. How astonished he would have been at its stunning, twisted terrain as radioed back by *Voyager 2*. Another moon he discovered, Nereid of Neptune, will be revealed to us for the first time later this summer. Among the many discoveries, definite or probable, made by *Voyager* are the repeated formation and destruction of moons and rings, the volcanism of Io, the configuration of outer-planet magnetospheres, the rich organic chemistry in the outer solar system—especially Titan's—and the possible existence of oceans on Titan and Europa.

The spacecraft have opened most of the solar system—both in extent and in mass—to the human species. They represent a triumph of American technology, admired even by those who have deep misgivings about other policies of our nation. They provide an example of what contemporary human technology, freed to pursue peaceful exploratory objectives, is capable. The data are made freely available, much of it in real time, to all the citizens of our planet. Those who built and operated *Voyager*—especially the engineering staff at the Jet Propulsion Laboratory, who time and again devised brilliant solutions to unexpected problems uncovered when the spacecraft, in effect, radioed home for help—deserve our respect and admiration. They are real American heroes.

Meanwhile, at almost a million miles a day, the two spacecraft are sweeping past the planetary part of the solar system. Their instruments may survive long enough to detect their passage through the heliopause, the charged-particle and magnetic-field boundary between the solar system and interstellar space. Inexorably, they will enter interstellar space and wander forever in the dark between the stars. Because interstellar space is such a benign and placid medium, the rate of erosion of the *Voyager* spacecraft will be very slow. Even a billion years from now, the two spacecraft will be very much as they are today (although, of course, inoperative). If there are interstellar spacefaring civilizations, it is possible that sometime in the next billion years one or both of the spacecraft will be intercepted and examined. To prepare for such a contingency, each of the spacecraft has, affixed to its side, a golden phonograph record (and instructions for use), containing greetings from our civilization, as well as a variety of information about our science, our technology, our music (90 minutes of "Earth's Greatest Hits"), our evolution and ourselves. Both in their exploratory mission and in the messages that they carry, these spacecraft are for the ages.

Neptune is the final port of call on *Voyager*'s Grand Tour. There are no more worlds on its itinerary. Before *Voyager 2* passes the planetary frontier into interstellar space, it has the opportunity to take (as I very much hope it will) one last picture—over its shoulder, of the inner solar system. The planets will appear as a sparse sprinkling of points of light. One of them, a tiny blue dot set against the spangle of the Milky Way, will be the Earth. From the distance of Neptune, it will seem no more than a faint star. I believe that this picture could have a profound influence on how we view ourselves, as powerful as the images taken by the *Apollo* astronauts of our lovely, finite and fragile planetary home.

Carl Sagan of Cornell University, President of The Planetary Society, is Distinguished Visiting Scientist at the Jet Propulsion Laboratory and a member of the Voyager *imaging team. He also chaired the NASA committee that designed and fabricated the* Voyager *Interstellar Record.*

Members' Dialogue

In the last issue of* The Planetary Report, *we promised that Academician Roald Z. Sagdeev, Scientific Director of the* Phobos *mission, would comment on the failure of both of the mission's spacecraft. Time constraints prevented Sagdeev from completing his statement, but he suggested we reprint instead selections from this article by K. Gringauz, which originally appeared in* Pravda. *The translation is by Colleen B. London of the Space Physics Research Laboratory of the University of Michigan.

The only new type of spacecraft developed by the industry in recent years for planetary research—the *Phobos*—was launched in the middle of 1988. (The *Vega* spacecraft are a modification of the earlier *Venera* series.) From the point of view of carrying scientific experiments, it has a number of shortcomings: It is difficult to put scientific equipment onto it in the necessary manner, the amount of transmitted information is not enough, and the scientific payload is too small in relation to its overall weight.

These shortcomings are connected with an unjust and inappropriate relationship between the Academy of Sciences and the aerospace industry. The chief designer of spacecraft, Academician S. P. Korolov, was well-aquainted with all the members of the academy's institutes who put experiments on the spacecraft of his OKB (Special Designing Bureau), and, at the time of the design of the spacecraft, he was in constant communication with them. His coworkers' thinking was in accord with the physicists', because they were solving the same problems. The same style was maintained by G. N. Babakin, to whom Korolov transferred from his bureau the designs of planetary spacecraft.

In the years of stagnation [when Brezhnev was Party Secretary], everything gradually changed. Now the Institute of Space Research finds itself in the position of a junior and (almost powerless) partner. The heads of the industry determine on their own the configuration of a spacecraft, the characteristics of its service system, the weight and energy consumption of the scientific equipment, and then they come to the Institute of Space Research with the proposal: Take it or leave it; that's all there is or will be. One gets the impression that the fewer the experiments the scientists come up with, the happier the heads of the industry are. . . . We should note that the loss of the first *Phobos* spacecraft . . . is connected with human incompetence and irresponsibility and not with any technical malfunction. The Academy of Sciences has no choice but to make peace with this situation, since it doesn't have any means of control of the industry which builds the spacecraft. . . . In this case, the producer dictates what is made. If these funds were given to the Academy of Sciences, and if the construction offices of the Soviet Space Agency were financially motivated to produce what the customer wanted, the technical quality of Soviet spacecraft and their ground testing would, without a doubt, greatly improve.

The design and implementation of the *Energia* and *Buran* systems entailed the surmounting of enormous difficulties, and they are the outstanding pride of engineering accomplishment. But they are only an engineering feat. To lump together these expenditures with those of basic scientific research is totally without justification. And to answer the question as to why we needed to have this system at the present time is certainly not easy.

At the international forum in Moscow on the occasion of the thirtieth anniversary of the launch of the first *Sputnik*, there was announced an impressive program for Soviet research on Mars (for the next decade, using unmanned spacecraft). However, its accomplishment is starting with astonishing sluggishness. Thus, for example, the development of the scientific equipment for the *Mars '94* spacecraft (which is supposed to be launched in 1994, with the same design as that of the *Phobos* spacecraft) has not yet even begun. This in spite of the fact that in the rest of the world they are already intensively working on the development of equipment designated for launches in 1995 or 1996. The period necessary for design and development of scientific equipment to be carried on board spacecraft is normally five to six years. The delay of work on the *Mars '94* project, which will result in a decline in the quality of the research, clearly appears to be of very little concern for the industry and equally as little for the Presidium of the Academy of Sciences.

All of this goes to show that the continuation of basic space research, initiated with such brilliance in our country, is currently arousing a deep concern, and the plans for building spacecraft for scientific research and manned spaceships need to be fundamentally readjusted.

In the USA the budget and the programs for space research are publicly examined and voted on by the Congress. It would be wonderful if such a system were introduced by the new Supreme Soviet of the USSR which will be elected this year.

—K. Gringauz, Chief Scientist, Space Research Institute, Academy of Sciences of the USSR

NEWS BRIEFS

Senator Albert Gore Jr. (D-TN) charges that Bush administration officials "censored" a scientist's planned testimony on global warming to downplay the problem. Dr. James E. Hansen, director of NASA's Goddard Institute for Space Studies, told *The New York Times* that the Office of Management and Budget edited his testimony to soften the conclusions and make the prospects of climatic change appear more uncertain.

"It distresses me that they put words in my mouth: they even put it in the first person," Hansen told the newspaper, adding that he had tried to "negotiate" with the budget office over the wording but "they refused to change."

—from the Associated Press

Many American adults suffer from "cosmic illiteracy" according to a nationwide survey taken by researchers from the Massachusetts Institute of Technology and Northern Illinois University. Out of the 1,111 adults polled, only 55 percent knew that the Sun is a star, only 37 percent believe that the Sun will eventually burn out and only 24 percent were aware that the universe is expanding.

When asked if the Sun is "a planet, a star or something else," 25 percent said the Sun is a planet, 15 percent said it was "something else" and 5 percent had no idea whatsoever.

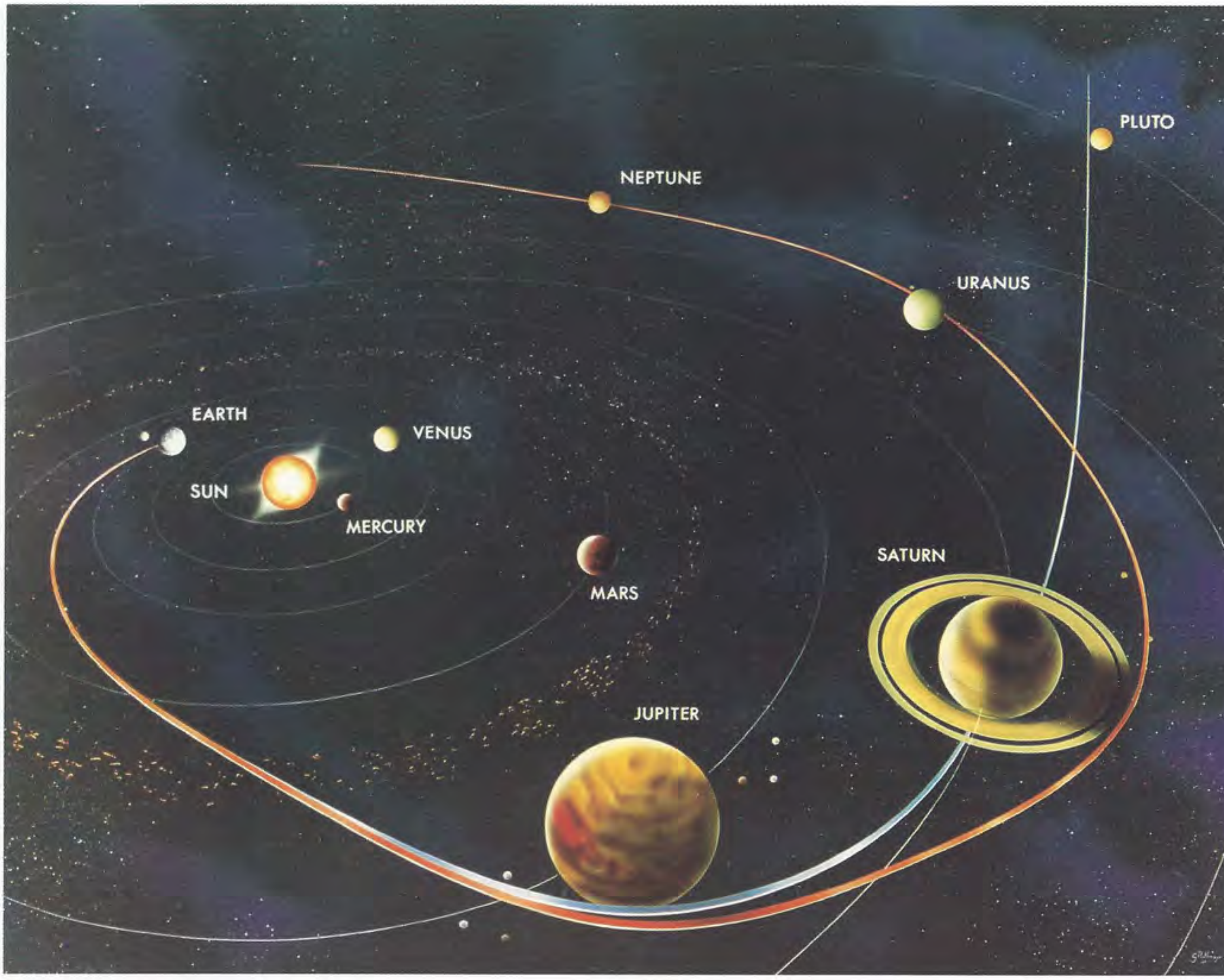
—from the *Los Angeles Times*

"The editors of *Popular Science* believe that if spending is to stay at or near current levels, we should build and expand our programs of monitoring Earth from space and sending scientific probes throughout the solar system and beyond.

"But we also believe that it would be in the best interest of the country and the world if we were to launch a 30-year program leading to the manned exploration of Mars in cooperation with the Soviet Union and other governments. A space station is a necessary intermediate step. Such a program would give a sense of national purpose and a scientific bonanza, and it would improve the chances of world peace."

—from an editorial by C. P. Gilmore in *Popular Science*

PUTTING VOYAGER TOGETHER



As originally envisioned, the Grand Tour of the outer planets would have begun with a launch to Jupiter, Saturn and Pluto in the mid-1970s, followed by a launch to Jupiter, Uranus and Neptune in 1979. Political and budgetary problems forced planners to scale back to one launch to Jupiter and Saturn (Voyager 1) and another to Jupiter and Saturn with possible flybys —if everything went exactly right—of Uranus and Neptune (Voyager 2).

Painting: JPL/NASA

Voyager 2 is about to stage another planetary spectacular by flying through the neptunian system in late August, transforming that distant and dark region from obscure to familiar. Since the flamboyant flybys of Jupiter in 1979, we have come to expect a reliable flow of scientific information from the *Voyager* spacecraft. But the path from the 1960s proposal of a "Grand Tour" to the mature project of the last ten years had many twists. Techniques and technologies had to be developed. Barriers of program definition and funding had to be scaled. And the early phase of flight operations can only be described as "scary."

Gravity Assists

The gravity-assist technique used by *Voyager* trajectory designers to pass their spacecraft from planet to planet had its intellectual roots in the venerable study of comets. By the 19th century astronomers realized that a comet could, on its looping orbit across half the solar system, pass close to a planet, and that the comet's orbit would be significantly altered as a result, especially if the planet were massive Jupiter. The change of trajectory could be so great that an unwary astronomer might fail to recognize the comet as one and the same object when observed before and after a close jovian encounter.

In 1889 the French astronomer François Tisserand published a simple mathematical method for assessing comet trajectories before and after a close planetary encounter. The creative leap that made *Voyager* possible—from Tisserand's criterion to the engineering utilization of gravity assist for a spacecraft—was accomplished by a series of trajectory analysts working on the *Mariner* and *Apollo* programs. A tip of the cap is due also to science fiction writer Lester del Rey, who forecast the technique in 1939.

The idea behind a gravity assist is simple. Pass the spacecraft behind a planet (or natural satellite) and the slight gravitational tug of the vehicle will subtract from the planet a minute

by William I. McLaughlin

amount of energy, which, by the law of conservation of energy, is then added to the spacecraft. The effects of this exchange, while slight for the planet, can be dramatic for the much less massive spacecraft.

A second effect from gravity assist is a bending of the spacecraft's trajectory by the gravitational pull of the planet. Thus, by careful selection of an "aim point" near the assisting planet, the spacecraft can gain energy *and* change course. Either of these maneuvers would otherwise require expending precious propellant.

The gravity-assist technique was employed during some of the *Apollo* flights when the spent third-stage of the *Saturn V* launch vehicle was directed to an aim point near the Moon and slung into an orbit about the Sun. The first planetary application of this method occurred in 1974 when *Mariner 10* was directed toward Mercury by means of an encounter with Venus. The *Voyager* concept of planet-hopping by means of successive gravity assists required careful planning and just the right conditions in the solar system—there is a shopworn joke that the administrations of John Adams and Thomas Jefferson missed an opportunity for the Grand Tour when the outer planets were last favorably aligned for successive gravity assists.

Technology Development

In the late 1960s, as the *Apollo* lunar-landing program was approaching culmination, NASA looked to the outer planets and initiated two projects: the *Pioneer* missions to Jupiter and Saturn, at the Ames Research Center, and the Thermo-electric Outer Planets Spacecraft (TOPS) project, at the Jet Propulsion Laboratory.

The two *Pioneer* spacecraft, launched in 1972 and 1973, are still functioning and returning scientific data from the outer solar system. In addition to exploring Jupiter (*Pioneer 10* in 1973 and *Pioneer 11* in 1974) and Saturn (*Pioneer 11* in 1979), these durable spacecraft lived up to their name by sampling the space environment and reporting data that would prove valuable in planning the more ambitious *Voyager* explorations. The *Pioneers* gave warnings of the intense flux of high-energy trapped particles in the jovian magnetosphere, and they alleviated fears over the dangers that might lurk in the asteroid belt.

The TOPS project addressed some key issues that had to be resolved before voyaging into the outer solar system. The generation of electricity for spacecraft subsystems was one such problem. Conversion of sunlight to electrical power, which had been employed on flights through the inner solar system, was not feasible for missions to Jupiter and beyond. The "Thermo-electric" in the TOPS acronym referred to production of electrical power from the heat generated by radioactive decay; this technology was the precursor of the radioisotope thermoelectric generators (RTGs) that now keep both *Voyagers* and the *Pioneers* supplied with power.

Returning images from deep space required development of a new telecommunications system of considerable channel capacity. A high-frequency (X-band) system was devised so that all of the information in a picture taken by the spacecraft's camera could be returned to Earth in just a few minutes of transmission time even at the range of Saturn. The X-band system allows the energy pattern radiated by the distant spacecraft to be focused toward Earth rather than spread over a larger region of space.

Traditionally, interplanetary spacecraft had been navigated by interpreting signals from their radio systems. To carry out its complex mission plan, *Voyager* needed to "see for itself," and so through "optical navigation" the spacecraft's camera measures planetary and satellite images

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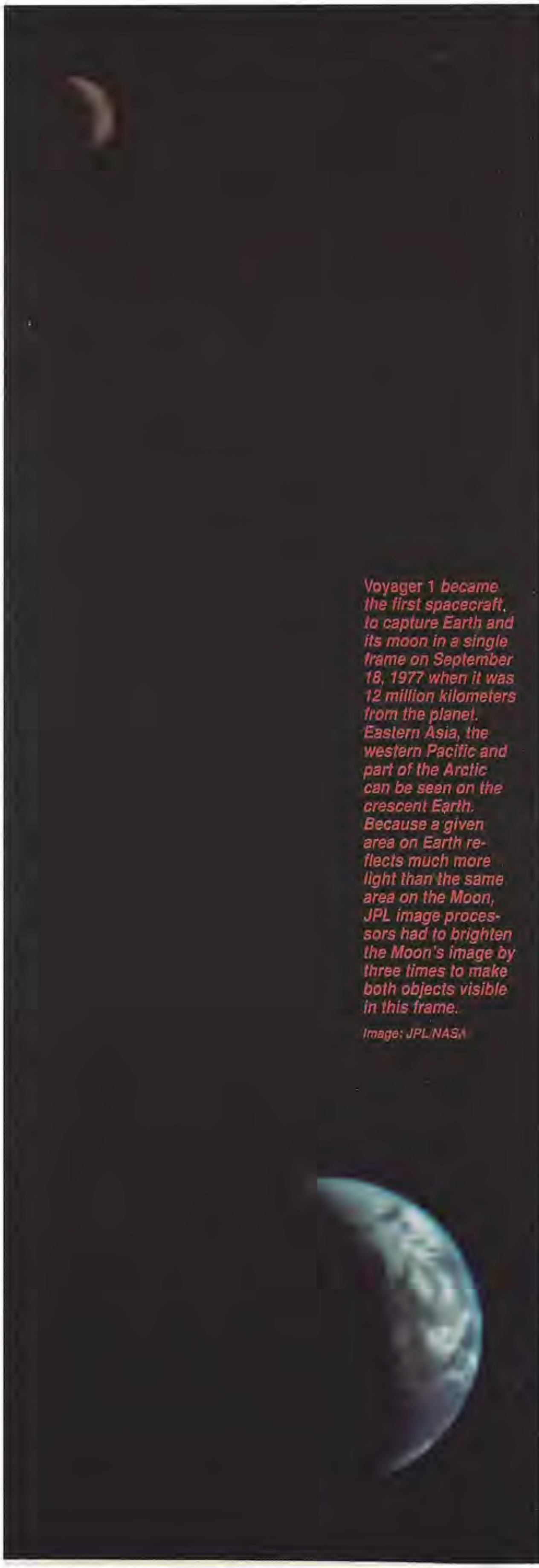
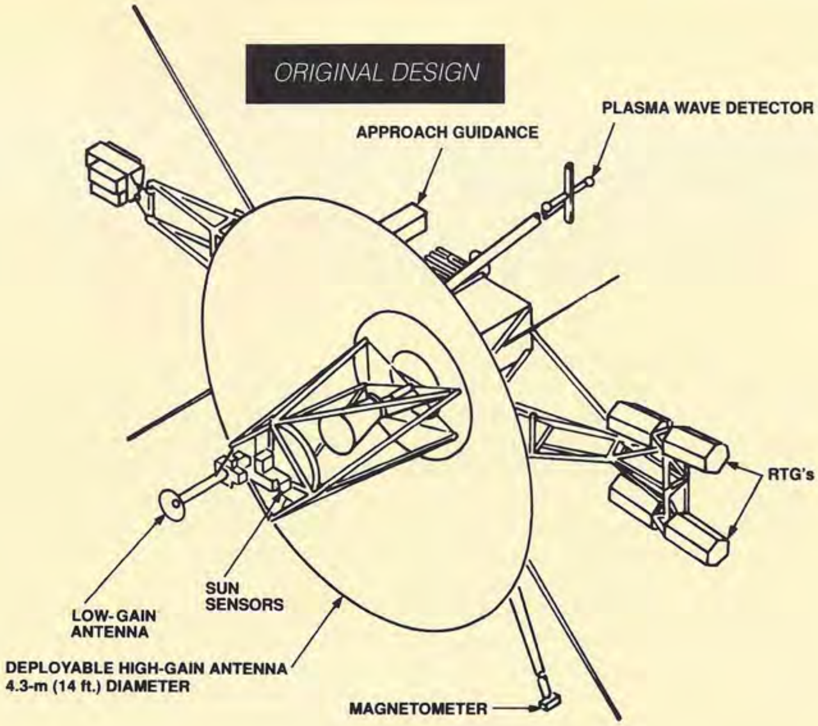


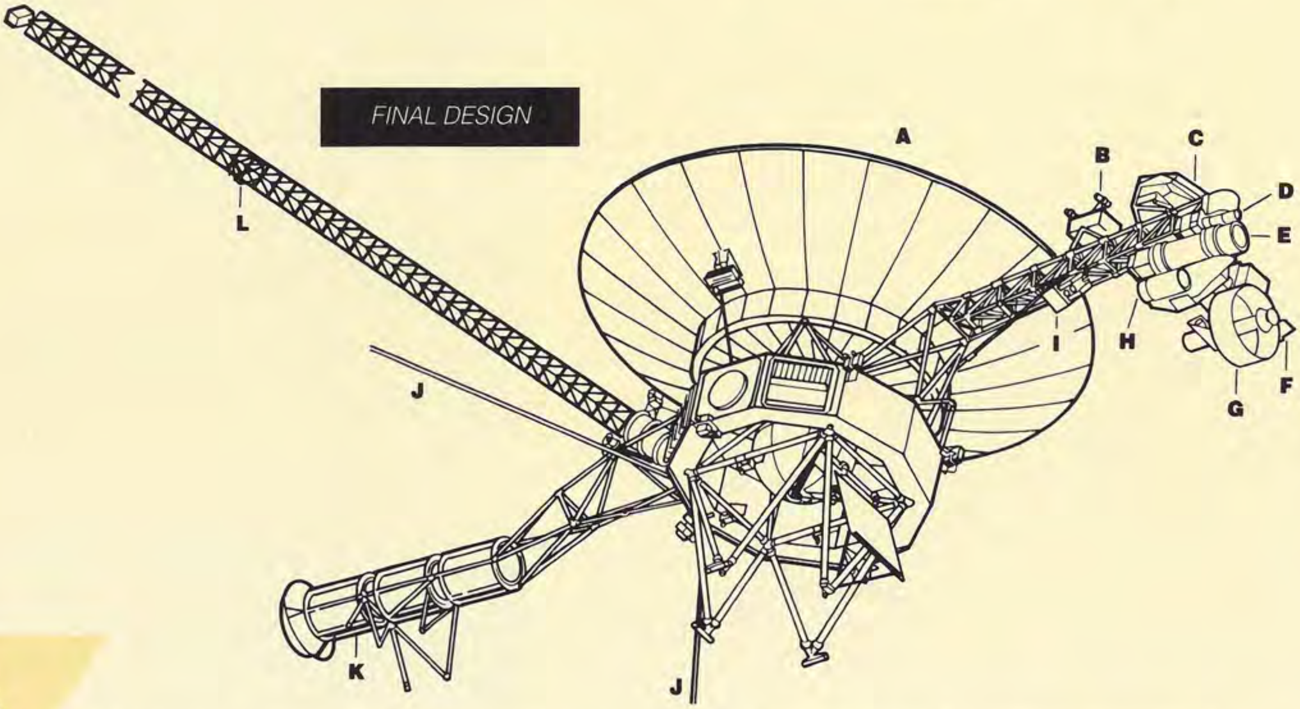
Voyager 1 *became the first spacecraft, to capture Earth and its moon in a single frame on September 18, 1977 when it was 12 million kilometers from the planet. Eastern Asia, the western Pacific and part of the Arctic can be seen on the crescent Earth. Because a given area on Earth reflects much more light than the same area on the Moon, JPL image processors had to brighten the Moon's image by three times to make both objects visible in this frame.*

Image: JPL/NASA

The Voyager spacecraft evolved from an early design done at the Jet Propulsion Laboratory called the "Thermo-electric Outer Planets Spacecraft" or TOPS (right). The spacecraft that finally flew (below) is now a familiar friend to the millions of people who have followed its odyssey through our solar system.

Drawings: JPL/NASA





A High-gain antenna—To communicate with Earth and to measure structure of atmospheres and rings as radio beam passes through them. The antenna is 3.65 meters (12 feet) in diameter.

B Cosmic Ray Detector—To intercept cosmic rays, atomic nuclei and electrons thought to be the most energetic particles in nature.

C Plasma Detector—To characterize properties of plasmas (hot, ionized gases affected by magnetic fields). Also determines properties of the solar wind.

D Imaging System, Wide-Angle Camera—Camera and refracting telescope to provide wide views of planetary objects.

E Imaging System, Narrow-Angle Camera—Telephoto camera and reflecting telescope for close-up views of planetary objects.

F Ultraviolet Spectrometer—To study the chemical composition, temperature and structure of atmospheres, and to study ultraviolet light from stars.

G Infrared Spectrometer and Radiometer—To measure the temperatures of planets and satellites. Can determine molecular composition of atmospheres and measure solar radiation reflected from a body.

H Photopolarimeter—To record the scattering of light by an atmosphere or surface. Also measures intensity of starlight passing through rings to determine structure and amount of material present.

I Low-Energy Charged Particles Detector—To measure composition and energy spectrum of low-energy charged particles trapped in planetary magnetospheres. Also measures the distribution and variation of galactic cosmic rays.

J Planetary Radio Astronomy and Plasma Wave Antennas—To detect radio emissions from charged particles in planetary magnetospheres, and from lightning in atmospheres. Also measures plasma waves in magnetospheres and detects interactions between magnetospheres and solar wind. Can "hear" collisions of small particles with the spacecraft.

K Radioisotope Thermoelectric Generators—Power plant for spacecraft, producing electrical energy through conversion of heat from radioactive decay of plutonium 238.

L Magnetometer—To characterize magnetic fields, structure of magnetospheres and magnetospheric interactions with moons.

(continued from page 5)

against a stellar background. Optical navigation is important because it establishes the location of the vehicle relative to the targets (rather than relative to Earth only). *Voyager* was the first US mission that absolutely required optical navigation to meet its scientific objectives, but as early as 1969 and 1971 the *Mariner* missions to Mars tried it out in preparation for exploration of the outer planets. The *Viking* missions to the Red Planet, launched in 1975, perfected optical navigation for *Voyager*.

Five Planets, Five Spacecraft

Human curiosity is a powerful force that has led us from Stone Age caves to the brink of interstellar travel. Curiosity about the outer solar system prompted a 1969 study by the Space Science Board of the National Academy of Sciences. The study recommended that the United States undertake an investigation of the outer planets, which would be in a favorable alignment in the late 1970s. A 1971 Academy study echoed the sentiment and developed the theme.

The plan for the Grand Tour was to launch four spacecraft to visit a total of five planets—that is, two spacecraft and one planet more than was eventually accomplished. The launches were to have been broken into two sets, with two spacecraft being sent to Jupiter, Saturn and Pluto in 1976 and 1977 and two sent to Jupiter, Uranus and Neptune in 1979. (An earlier version of the plan featured five spacecraft to explore the outer planets.)

Budget pressures began to build within NASA, causing the agency to search for ways to decrease the scope of the mission and reduce its cost. A compromise was reached that proposed a prime mission to Jupiter and Saturn, to be accomplished by launching two spacecraft in 1977. A third spacecraft would be launched in 1979 to visit Jupiter and Uranus.

The "*Mariner*-Jupiter-Saturn" project, "MJS77" for short, was approved by Congress in 1972 and became the *Voyager* Project that we know today, with the name change taking place early in 1977, before launch. The 1979 mission, "MJU79," fell by the wayside despite strenuous efforts by the late Jim Long and others at JPL.

Mission designers for MJS77 were well aware that at Saturn, the presumptive end point of the mission, it would still be possible to resuscitate the Grand Tour and send the spacecraft on to Uranus and Neptune. That option was not exercised with *Voyager 1*. Scientific interest in Titan, Saturn's largest satellite, dictated that *Voyager 1* be sent on a trajectory that precluded the needed gravity assist for a Uranus flyby. But *Voyager 2* threaded all four pearls—Jupiter, Saturn, Uranus and Neptune —on the string of its flight path. It is not dynamically possible to arrange a gravity assist at Neptune that would send *Voyager 2* to Pluto.

Just Getting to Jupiter

Today the *Voyager* flight team functions with a quiet confidence derived from 12 years of successful operations. Success didn't come easy in the beginning.

Voyager 2 lifted off from Kennedy Space Center on August 20, 1977 atop a *Titan 3-E/Centaur* launch vehicle. The launch of *Voyager 1* followed on September 5 (numerical order in the mission was restored when *Voyager 1* arrived at Jupiter four months ahead of *Voyager 2*).

Voyager 2 was the troublesome twin. Even before launch, failures in its onboard computer subsystems had to be rectified. The problems continued after liftoff as the attitude-control subsystem behaved in an unexpected fashion. Newspaper headlines spoke anthropomorphically of a "Mutiny in Space." Then there was concern that the boom holding the platform on which the remote-sensing instruments were mounted, including the camera, was not fully deployed.

One by one these problems were sorted out by the mission flight team, and *Voyager 2* seemed to have emerged from its chrysalis of troubles. But in the spring of 1978 the most fearful blow fell: The primary radio receiver failed. The spacecraft switched to its backup receiver, which was found to be severely flawed (due to a faulty tracking-loop capacitor). In effect the range of frequencies on which *Voyager 2* could receive instructions was greatly reduced; to make matters worse, this narrowed receiving bandwidth kept shifting with even small changes in the temperature of the spacecraft. All communication with *Voyager 2* could have been lost, leaving it to drift helplessly through the solar system.

The engineering teams rapidly put together a new system by which they could fit commands into *Voyager 2*'s elusive range of reception. Communicating with *Voyager 2* is a skill that the flight team must continue to practice even today.

On September 5, 1977, a* Titan 3 *rocket carrying a* Centaur *upper stage launched* Voyager 1 *from Kennedy Space Center toward Jupiter and Saturn.

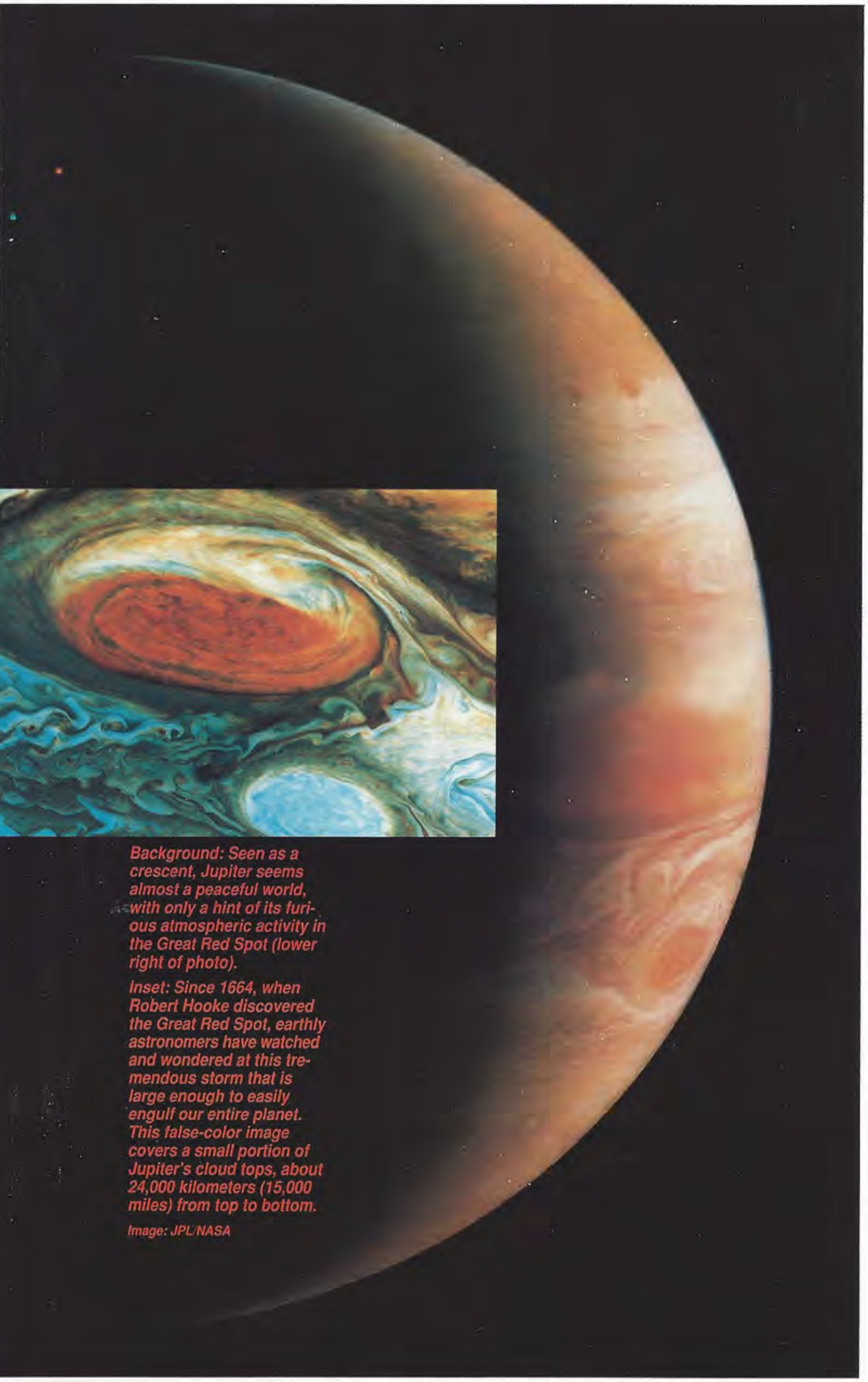
Photograph: JPL/NASA

Within a short time the flight team had installed a Backup Mission Load (BML), a sequence of commands that provides some insurance against further problems with the radio. Even if the command link is lost, BML will ask *Voyager 2* to execute a minimal program of observations at Neptune and send the results automatically back to Earth.

The Grand Tour draws to a close. Will this greatest of space explorations seem as magnificent to future generations as it does to us, who watch in wonder? Bet on it.

William I. McLaughlin was manager of the Flight Engineering Office for the Voyager/*Uranus mission and is currently manager of the Mission Profile and Sequencing Section at the Jet Propulsion Laboratory.*

JUPITER: FIRST STOP ON



Background: Seen as a crescent, Jupiter seems almost a peaceful world, with only a hint of its furious atmospheric activity in the Great Red Spot (lower right of photo).

Inset: Since 1664, when Robert Hooke discovered the Great Red Spot, earthly astronomers have watched and wondered at this tremendous storm that is large enough to easily engulf our entire planet. This false-color image covers a small portion of Jupiter's cloud tops, about 24,000 kilometers (15,000 miles) from top to bottom.

Image: JPL/NASA

Jupiter, with its dazzling satellite system, was the first target in the epic journey of the *Voyager* spacecraft. Jupiter is the giant of the planets, with more mass than all of the other eight planets combined. Its powerful gravity has clung to the primordial gases hydrogen and helium, giving Jupiter a composition similar to that of the Sun and stars.

The chemistry of Jupiter is dominated by hydrogen and its compounds, such as water, ammonia and methane. Swirling ammonia clouds float high in its extensive atmosphere. Its interior is primarily liquid hydrogen at a high temperature, with no solid surface.

Although it is immense relative to the other planets, Jupiter's mass doesn't compare with that of a star. In order to sustain a star's internal nuclear reactions, the planet would require nearly 70 times more mass. However, Jupiter does radiate substantial heat in the infrared part of the spectrum. Its interior is still hot as a result of gravitational energy released when the planet formed out of the solar nebula some 4.5 billion years ago.

Even before *Voyager*, we knew the basics of Jupiter's size and composition. Further, radio astronomers had mapped Jupiter's huge magnetosphere of charged particles, trapped in a magnetic field stronger than that of any other planet. Close-up observations of magnetospheric and atmospheric phenomena were prime objectives of the *Voyager* flybys, but we also wanted a good look at the giant planet's array of moons.

Jupiter is at the center of its own miniature "solar system." Among the 13 satellites that we knew about before *Voyager*, the four known as the Galilean satellites are larger than our Moon. The largest, Ganymede, is nearly as big as Mars. From telescopic measurements, astronomers had determined that the outer two Galilean satellites —Callisto and Ganymede—are composed in large part of water ice, while the smaller inner satellites—Io and Europa—are primarily silicate in composition, like the terrestrial planets. Little more was known about these worlds until the revelations of the *Voyagers*.

VOYAGER'S GRAND TOUR

by David Morrison

Closing In

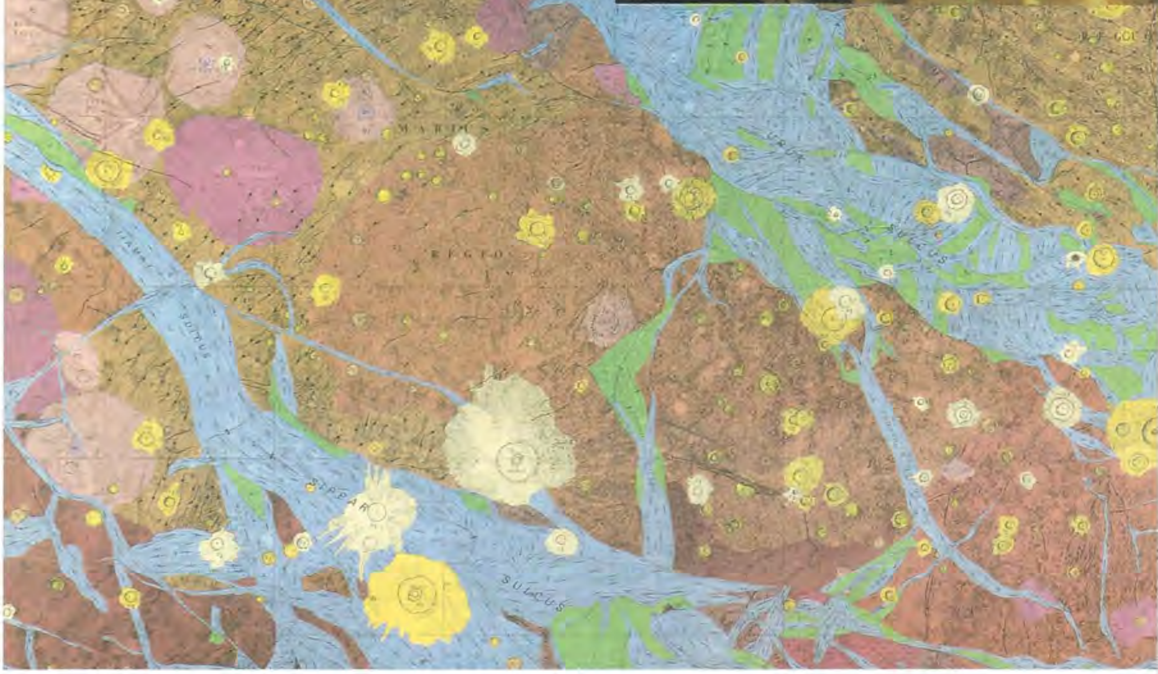
Voyager 1 flew a long curving trajectory that took it past the planet on March 5, 1979 just 270,000 kilometers (170,000 miles) above the cloud tops. Its path through the satellite system was calculated to permit close examination of Callisto, Ganymede and Io during the preceding days. At a range of just 22,000 kilometers (14,000 miles), the Io flyby was close enough for imaging objects as small as one kilometer (0.6 mile) over much of the satellite surface.

Following a similar path, *Voyager 2* reached Jupiter on July 9, after encounters with Callisto, Ganymede and Europa. The best *Voyager 2* satellite flyby took in Ganymede at a range of 62,000 kilometers (39,000 miles). The path of each spacecraft was exactly adjusted so that the powerful gravity of Jupiter would accelerate them on toward Saturn, the next target.

For several months before encounter, *Voyager 1* photographed the complex cloud motions in Jupiter's atmosphere to generate a "movie" for analysis of atmospheric circulation. Then, beginning about fifteen days before the flyby, the full battery of *Voyager* instruments began their measurements of the planet, its satellites and the space through which the craft was passing. Each day the precision and resolution of the planetary measurements improved, generating a wealth of new data for the *Voyager* scientists to interpret. The usually deliberate pace of scientific investigation accelerated, with new theories being created and either reinforced or disproved within a matter of days, or sometimes hours.

On February 28, 1979 *Voyager 1* reached the boundary of Jupiter's magnetosphere, and the encounter period began. Previously, the craft had been in the interplanetary medium, measuring properties of the solar wind streaming out from the Sun. Now it began to study the magnetic field of the jovian system. At first, rapidly changing pressure from the solar wind caused the highly elastic magnetosphere to swell and contract several times, and it was not until March 3, at a distance of about 3 million kilometers (2 million miles), or 47 Jupiter radii, that *Voyager 1* finally crossed the magnetospheric boundary for good. Two days later the spacecraft reached the orbit of Callisto, the outermost of the four

Right: The erupting sulfur volcanoes of Jupiter's moon Io were among the most astonishing discoveries of the Voyager mission. Caught between the gravitational pulls of sister satellite Europa and the immense planet, Io is heated by tides that drive the most active volcanism yet seen in our solar system. The plume seen here is erupting from the volcano Loki.



Below: Years after the Voyager spacecraft passed through the jovian system, researchers on Earth are continuing to examine the data and glean more knowledge about these strange worlds. This map of Ganymede, the largest moon yet visited in our solar system, reveals varied terrains. Ganymede displays dark, heavily cratered regions and strange, grooved features that are unique to this world.

Image and Map: US Geological Survey, Flagstaff

Galilean satellites. And from there on, discovery piled upon discovery at a dizzying pace.

A Ring and 3 New Moons

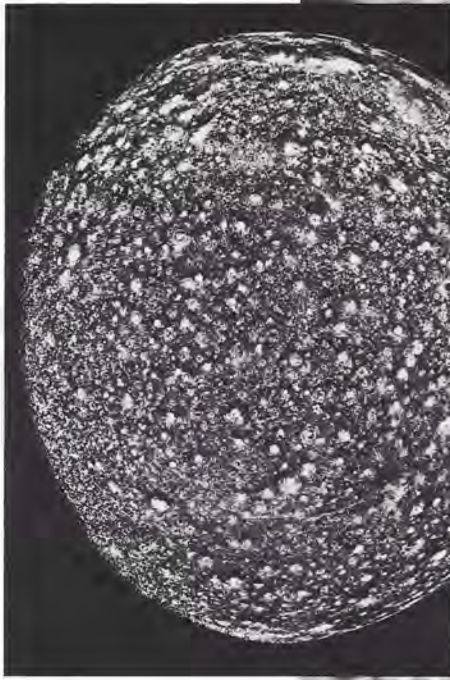
As it swept through the jovian system, the spacecraft's instruments described the complexities of the magnetosphere. Because it is closely coupled to Jupiter's magnetic field, the inner parts of the magnetosphere rotate with the same 10-hour period as the planet, accelerating the trapped charged-particles to tremendous speeds. Radiation from charged particles striking the spacecraft increased steadily until the moment of closest approach to Jupiter, near the orbit of Io, the inner Galilean satellite.

Io is coupled to Jupiter by a loop of intense electrical current called the Io flux tube. *Voyager 1* steered right through this flux tube, measuring the strength of the current.

At about the same time, the spacecraft's cameras succeeded in photographing what turned out to be a ring of dust circling Jupiter. The search for such a ring had been considered a long shot before the encounter, but there it was, confined within the orbits of two small satellites, newly discovered by the *Voyager* cameras. The tiny ring particles, acquiring an electrical charge from the magnetosphere, spread above and below the planet's equator; thus Jupiter's ring is thicker than the flat rings of Saturn. A third small satellite was also discovered near the planet, bringing the total of jovian satellites to 16.

The two largest satellites of Jupiter—Ganymede and Callisto—being composed of about half water ice, represented a class of objects never before viewed at close range. Scientists expected that the geology of such ice-and-rock objects of planetary size would be different from the more familiar rocky worlds, and they were not disappointed.

Callisto, although lacking evidence of internal geological activity, displays a multitude of impact craters, some of them quite different from any impact features seen in the inner solar system. The simple fact that Callisto's surface is saturated with craters—that is, the total number of craters cannot increase, because any new impact would have to destroy an existing crater—demonstrates that early in its history the outer solar system experienced a high rate of impacts, perhaps analogous to the late heavy bombardment of the inner planets as recorded in the heavily cratered highlands of the Moon.



Right: Callisto, the outermost of the Galilean satellites (Io, Europa, Ganymede and Callisto, all discovered by Galileo), is probably the most heavily cratered body in our solar system. As this enhanced-contrast image shows, its face is "saturated" with craters; crater is piled upon crater, so that each crater formed by an impact destroys another crater. ***Image: JPL/NASA***

Far right: The smallest moon of Jupiter is possibly the most intriguing. Long dark cracks mar its smooth, icy surface. Few of the impact craters that cover most solar system satellites are visible on Europa. Some as yet unknown process is keeping this moon's face smooth. Some scientists have speculated that an ocean of liquid water may lie under Europa's thin ice crust, and when a meteorite or comet strikes the surface, traces of its impact are erased by water oozing into the resulting crater.

Map: US Geological Survey, Flagstaff

Ganymede's surface preserves the record of a complex history of melting, mountain formation, and slow evolution of the thickness and strength of its crust.

Europa, observed from afar, remained an enigma to *Voyager 1*. It would be studied in better detail four months later by *Voyager 2*.

Live Volcanoes

The most spectacular result of the *Voyager 1* Jupiter flyby was the discovery of intense volcanic activity on Io, a satellite distorted and heated by the effects of tides raised by Jupiter. A few weeks before the encounter, three astronomers had calculated that Io might be tidally heated and had predicted that its surface would show evidence of volcanism. Sure enough, the spacecraft cameras photographed a strange, colorful topography, lacking in impact craters but showing many signs of past volcanic eruptions.

The big surprise came a few days after the encounter, when members of the *Voyager* navigation team found a faintly illuminated arc above the satellite in one of their long-exposure pictures. This unexpected feature turned out to be one of eight active eruptions captured in the photographic record, each fountaining sulfur and sulfur dioxide to a height of tens to hundreds of kilometers above the surface. The ejected sulfur and sulfur compounds condense in the cold of space and fall back to blanket the surface, painting it a variety of colors from white through shades of orange to red.

Voyager 1 also recorded heat radiation from the volcanoes. The strongest of the Io "hot spots" was a sort of lava lake called Loki, about 200 kilometers (125 miles) across, with the "lava" probably composed of liquid sulfur. Little Io, no larger than Earth's Moon, turned out to have the most active geology and the highest level of volcanism of any body in the solar system.

Atmosphere and Local Color

Although much attention was focused on discoveries concerning the satellites, the magnetosphere and the ring of Jupiter, the planet itself proved to be of exceptional interest. Its colorful atmosphere is in constant motion, displaying a wide variety of storms, jet streams and other meteorological phenomena.

Some features are reminiscent of atmospheric circulation on Earth, others are unique to this giant planet, whose atmosphere is driven by escaping internal heat as well as absorbed sunlight. The largest and best known feature is the Great Red Spot; the *Voyager* cameras and spectrometers showed that this storm, unlike terrestrial storms, is a circulating region of high atmospheric

pressure, rather than a low pressure region.

The sheer amount of detail was surprising, as high-resolution images of the atmosphere revealed a kaleidoscope of swirling colors, with relatively little mixing between adjacent features of different hues. Although we learned much about the atmosphere's composition and dynamics, its chemistry retains a fundamental mystery: We don't yet understand the chemical actions that impart such bright colors to the swirling jet streams and storms of this planet. Perhaps they are compounds of sulfur, perhaps organic chemicals produced by the action of ultraviolet light on the upper atmosphere. No one knows.

Infrared readings of Jupiter revealed that the second most abundant gas after hydrogen is helium, and thus the planet's bulk composition is the same as that of the Sun—75 percent hydrogen, 25 percent helium. Analysis of the temperature and structure of the atmosphere indicates that the high clouds are composed of frozen crystals of ammonia, and below we think there is a layer of ammonium hydrosulfide clouds. Further down, there may be clouds of water ice and water droplets like those on Earth. These unseen regions will be measured directly by the *Galileo* probe, scheduled for launch in October of this year.

Voyager 2*'s Turn*

Only four months separated *Voyager 2* from *Voyager 1*, and before the results of the first flyby could be fully processed, the observatory phase for the second spacecraft was under way. On July 2, 1979 *Voyager 2* entered the jovian magnetosphere at a distance from the planet of more than 5 million kilometers (3 million miles). The magnetosphere had expanded between encounters.

By July 6 long-range photos of Io confirmed that most of the active volcanoes discovered by *Voyager 1* were still erupting. On July 8 *Voyager 2* passed Callisto, and early the next day it obtained the best photos yet of Ganymede. While much of the surface of Ganymede appears to be old and heavily cratered terrain, as on Callisto, younger mountains cover about half of this moon. These may have been produced by alternating cycles of expansion and compression of the crust, resulting from the cooling that followed the formation of the satellite.

Europa, poorly imaged by *Voyager 1*, proved as extraordinary as its companion moons, with a smooth icy surface crossed by hundreds of light and dark lines that look like cracks in sea ice. Possibly this icy crust covers a global ocean of water. If so, Europa is the only place in the solar system beyond the Earth where extensive liquid water can be found. Here was another satellite with its own special geologic history and a visage different from any planet or moon previously investigated.

The four month interval between encounters proved ideal for investigating changes in the magnetosphere and circulation of the atmosphere, and it allowed sufficient time for us to adjust *Voyager 2*'s program after *Voyager 1*'s observations. *Voyager 2*'s photographs of the jovian ring were among the highlights of the July 9 encounter.

The two Jupiter encounters are rightly celebrated as splendid technological and scientific accomplishments. Following *Voyager 2*'s Jupiter encounter, NASA Associate Administrator for Space Science Thomas A. Mutch said, "We're starting a new stage of space exploration, and when history books are written a hundred or two hundred years from now, historians will cite this period of exploration as a turning point in our cultural, our scientific, our intellectual development." The success of the Saturn and Uranus encounters fully justified this optimistic assessment of the *Voyager* program. And now, Neptune beckons.

David Morrison is Chief of the Space Science Division, NASA Ames Research Center.

SATURN: JEWEL OF THE SOLAR

The saturnian system is unquestionably the most beautiful in our solar system. JPL image processors created this montage from images taken by both* Voyager *spacecraft. The satellites seen here are (clockwise from top right) Titan, Iapetus, Tethys, Mimas, Enceladus, Dione and Rhea.

Image: JPL/NASA

The *Voyager* Saturn encounters in November 1980 and August 1981 can leave little doubt as to the poverty of our collective scientific imagination and the absolute necessity for exploration. Naturally, we had our theories and our consensus wisdom. Based on these, we planned a variety of observation sequences months in advance and eagerly awaited the results. We knew we would get answers to some of our questions, and we knew there would be some surprises. But we had no clue as to the wealth of phenomena that would be revealed when the *Voyagers* entered the Saturn system.

Arriving at JPL (Jet Propulsion Laboratory) late in the evening a week before the *Voyager 1* encounter, I found the entire lab complex ablaze with lights and alive with throngs of people. Colleagues from across the country had gathered to get a little closer look at the new data and toss around ideas, and the international press corps was out in strength. There was a mood of festival in the air. A similar feeling pervaded the *Voyager 2* encounter nine months later.

Discoveries came at a fast and furious clip during both Saturn encounters. Much of the "instant science" that we all did in those hectic weeks has (mercifully) been forgotten, replaced by slower but steadier strides in the years that followed. In this article, there is only enough space for some of the highlights dealing with the rings, the icy satellites and Titan.

Grooved Rings, Not Smooth

Scientists have long thought the Saturn system to be rich in clues about the origin of the solar system, which evolved from a pancake-shaped "protoplanetary nebula" of gas and particles orbiting the forming Sun. Disks of particles, such as the rings of Saturn, provide an excellent laboratory for studying how the disk of dust and gas that ultimately became our planetary system was produced and distributed. Much current research on the evolution of the solar system derives directly from efforts to understand the beautiful and surprising patterns seen in Saturn's rings.

We were dazzled by the filigree structure of the rings of Saturn. The "record groove" radial structure of the rings was revealed to the *Voyager* cameras from as far as 10 million kilometers (6 million miles). Two photopolarimeter experiments picked up finer-scale structure, resolving features down to several hundred meters. In these experiments the instruments rapidly sampled the fluctuating brightness of the star delta Scorpii as the spacecraft's motion caused the star to trace a path through the shadow of Saturn on the rings. In addition to being an aesthetic bonanza, the extent and variety of all this ring structure was a scientific surprise.

Saturn's rings are made of icy particles in high-speed orbit around the planet. While orbiting Saturn at 3 kilometers per second (75,000 miles per hour), the ring particles jostle each other ever so gently—their typical collision velocity is millimeters per second. The large number of particles and their gentle collisions give the rings many of the characteristics of a fluid, notably viscosity, which is a prime contributor to ring structure. (Viscosity, the tendency of a fluid to resist flowing, is a manifestation of molecular friction, the result of a large number of particles and their collisions.) We had thought, incorrectly, that viscosity would prevent fine structure from forming.

Careful analysis of the light scattered by the rings, done in the years since encounter, has revealed that ring particle surfaces are more "compacted" in regions where collisions are more vigorous. The collisions pack the particle surfaces, much as one makes a snowball, but not so violently as to fragment the particles and produce clouds of dust (as we had thought during encounter). The degree of jostling determines the effectiveness of viscosity in creating and removing fine structure in the rings.

The cause of the irregular filigree structure, still unresolved, probably involves subtle and counter-intuitive

SYSTEM

by Jeffrey N. Cuzzi

ways in which viscosity can work in orbiting particle disks.

Bombarded Rings and "Spokes"

We have uncovered clues that small meteoroids—perhaps comet fragments—hit the rings at a very high velocity, typically 30 kilometers (19 miles) per second. At these velocities, an impact would be like the explosion of a hundred times the meteoroid's mass of TNT. Such energetic impacts may help explain one of the most mysterious discoveries made by *Voyager*—the "spokes" flickering across the B ring.

These huge features appear nearly instantaneously (in only a few minutes) yet cover tens of thousands of kilometers, and spread into wedgelike patterns that last for several hours before fading away. The spokes are probably generated by microscopic grains liberated from the surfaces of ring particles.

Exactly how this process works is still not understood. It may begin with a large cloud of charged gas, produced by a meteoroid impact, that moves across the rings, causing tiny grains to fly off the surface of their parent particle. It certainly involves some interactions with the planet's magnetic field as well as the still-hypothetical impact "trigger." We think that it takes a meteoroid with a radius between 10 centimeters and a meter (4 to 40 inches) to produce a spoke. Of course, meteoroids this large are not common; only the vast extent of the rings—their area is ten thousand times that of Earth—provides a screen large enough for watching this movie.

Warps in the Ring Plane

In addition to viscosity and meteoroid bombardment, gravity plays an important role in shaping the structure of the rings, notably in the nearly regular, wavelike features detected in the earliest *Voyager* images and in the stellar and radio occultation experiments.

In this case the data confirmed our pre-*Voyager* theoretical prediction that spiral density waves, such as delineate the arms of a spiral galaxy, would form at locations susceptible to the gravity of a massive moon (that is, locations where particle orbit periods were simple ratios of the satellite orbit period). Nevertheless, it took nearly two years for us to recognize other similar patterns as spiral "bending waves," or warps in the ring plane.

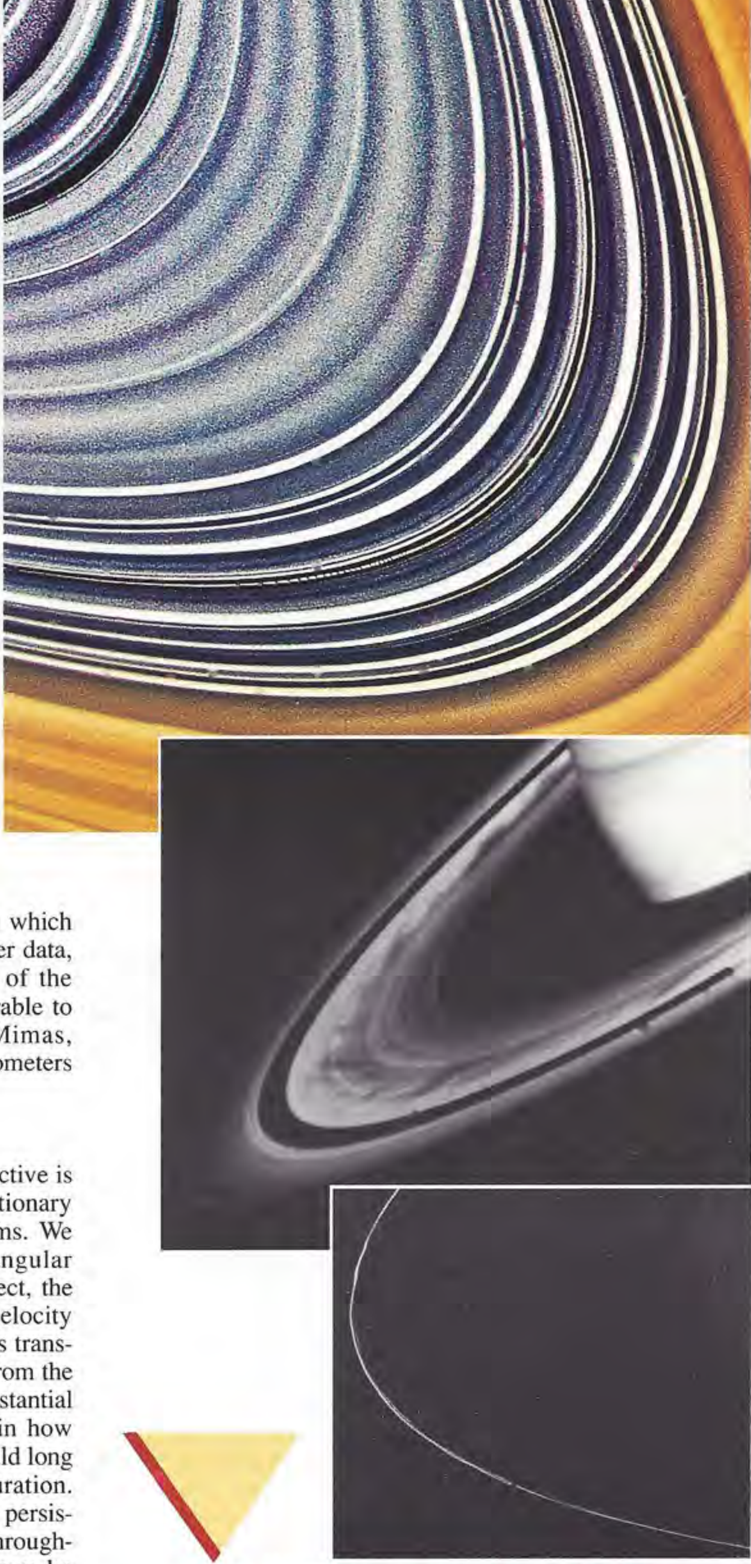
Over the eight or so years since the encounters, the spiral wave patterns have been studied in great detail, and we understand their theoretical basis well enough now to use them to determine the mass in the regions through which they travel. Using these and other data, we have determined the mass of the entire ring system to be comparable to that of the saturnian moon Mimas, which has a diameter of 400 kilometers (250 miles).

Young Rings

A fundamental change in perspective is emerging concerning the evolutionary time scales of ring-moon systems. We realized quite early on that angular momentum (for an orbiting object, the product of its mass times its velocity times its distance from Saturn) is transferred via spiral density waves from the rings to the moons at such a substantial rate that it is difficult to explain how either the rings or the moons could long endure in their current configuration. This was the first note in a now persistent refrain of indications that, throughout the solar system, rings may be much younger than their planets.

Another clue came indirectly from investigations of why there are so few electrons in Saturn's ionosphere (an upper atmospheric region characterized by an abundance of atoms with an electrical charge) as compared to the ionosphere of Jupiter. A flow of water molecules into Saturn's ionosphere from the apparent "atmosphere" enveloping the rings could account for this depletion, since water molecules are efficient

(continued on page 14)



Top: At Saturn, Voyager cameras revealed that the bright, broad, apparently smooth bands seen in telescopes were actually composed of thousands of thin "ringlets." This false-color image focuses on the boundary between two major differentiated sections called the B ring (yellow) and C ring (blue).

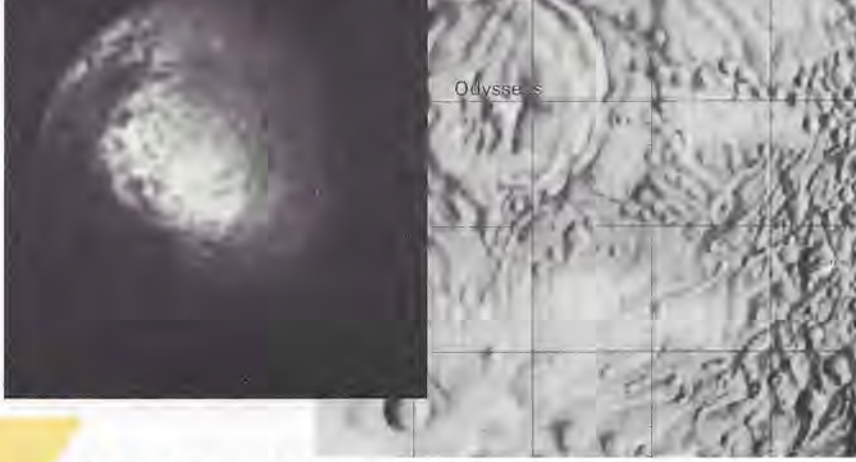
Middle: Another surprising discovery of the Voyager mission was the phenomenon of "spokes" in Saturn's rings, huge wedge-shaped features perhaps triggered by meteroid impact.

Bottom: The Voyagers revealed that the F ring outside Saturn's main ring system is kinked, with individual strands seemingly crossing each other. Gravitational interaction with small satellites traveling on either side of this ring may cause this strange structure.

Images: JPL/NASA

scavengers of electrons. However, the amount of water required to sustain this transfer over the age of the solar system would be comparable to the ring mass itself. A loss of mass on that scale creates a problem for survival of the rings.

Moreover, solving the ionosphere problem this way poses yet another puzzle. The only mechanism that could generate this much vapor seems to be micrometeoroid bombardment. Meteoritic impurities in the ring material, as measured by their reflection and emission of visible light and radio waves, are a small fraction of the amount of material that would have hit the rings over the age of the solar system, if the infall rate is as large as we suspect. This set of arguments thus also points to youthful rings. Similar arguments apply to the rings of Jupiter and Uranus. Recent formation of planetary rings, as we will see in a later section, bears on the possible co-evolution of rings and moons.



Left: Saturn's outermost large satellite, Iapetus, is a most peculiar world. The hemisphere that leads in its orbit around the planet is many times darker than its trailing hemisphere. The source of this dark—probably organic—material is a mystery. Some scientists believe that it fell onto the moon from other dark objects; others think that it erupted from beneath Iapetus' surface.

Middle: In this map of Tethys compiled from* Voyager *images, the giant impact crater Odysseus, about 400 kilometers (250 miles) across, dominates one face of the moon. On the opposite side Ithaca Chasma takes precedence. This feature was possibly formed by the same impact that created Odysseus.

Far Right: Perhaps no other satellite visited by* Voyager *aroused as much scientific interest as Titan.* Voyager 1 *found a rich array of organic molecules; these molecules coalesce in aerosol particles, forming haze layers (blue in this false-color image) and red, organic clouds. ***Images: JPL/NASA***

Old Moons

Impact craters are the dominant landform on the saturnian satellites—scars left over, primarily, from the early years of the solar system when the last few planetesimals, bodies up to 200 kilometers in size, were swept up on the hardening surfaces of newly formed moons and planets. (The incessant hail of tiny meteoroids now scouring the rings and moons is a remnant of this primordial torrent.) Many subtle inferences can be read in the cratering record, but controversies remain.

The bombardment history on the surfaces of Saturn's icy Mimas, Tethys, Rhea, Dione and Iapetus is manifestly different from that left on Jupiter's large moons, which have many more large craters. The large craters on Jupiter's moons were probably created by planetesimals coming from remote reaches of the early solar system, while the smaller craters on Saturn's moons may be a record of debris created within the Saturn system—possibly by the partial or complete destruction of other moons.

Whatever their cause, the craters blanketing Mimas, Tethys, Dione and Rhea are too plentiful to be recent; they probably record events occurring 3 to 4 billion years ago.

Enceladus the Exception

The surface of the small moon Enceladus, on the other hand, tells of more recent events. Close-up *Voyager* images show Enceladus to be nearly devoid of craters over much of its surface; instead, there are wavy patterns reminiscent of glacial flows. Its smoothed-over appearance means that the surface of Enceladus must be extremely recent —certainly less than a billion years old and maybe as young as "yesterday."

Of all the satellites in the solar system, Enceladus has the brightest surface. Because it remains unsullied by the continual infall of impurity-laden meteorites, we must again conclude that this bright, nearly pure icy surface is quite young. In another observation of a short-lived phenomenon, we have found that Enceladus is surrounded by a hazy belt (the E ring) of microscopic particles that are rapidly destroyed by magnetospheric and meteoritic erosion.

Taken together, the evidence suggests extremely recent resurfacing of Enceladus by some sort of ice flows. However, Enceladus has too few radioactive elements to heat itself substantially, and it is too small to hold heat for very long. We would not expect Enceladus to have a molten interior even if, like most other satellites, it turns out to have gone through a molten state at the time of its formation. Thus, the recent source of energy for the observed resurfacing remains a mystery.

Reassembled Moons

The concept of moons being destroyed occasionally during the history of the solar system has achieved new respectability since the Saturn encounters. Mimas, innermost of the satellites known before *Voyager*, was found to sport a huge crater, spanning nearly one-third of the moon's diameter. The martian moon Phobos is the only other object in the solar system to display a crater so large compared with its own size; just a slightly larger impact would have split Mimas into fragments.

Such may have been the fate of hamburger-shaped Hyperion, which tumbles erratically in its orbit, unlike all other close-in satellites, which constantly present the same face to the parent planet. Hyperion's tumbling, influenced by massive Titan, is an example of "chaotic" motion, being deterministic but unpredictable (see *The Planetary Report,* May/June 1989, for more on the study of chaos in the solar system).

We believe that Saturn's small inner satellites, with radii of 100 to 300 kilometers (60 to 200 miles), have been destroyed and reaccreted several times over, probably 3 to 4 billion years ago, when the last planetesimals were still being swept up.

Ringmoons

As hinted previously, we are beginning to realize that rings and moons are not isolated phenomena but blend smoothly into one another. *Voyager* imaged moonlets in and around the rings of Jupiter and Uranus and just outside the rings of Saturn. By analysis of disturbances in the nearby ring material, we can infer the presence of at least one other saturnian moon, about 10 kilometers (6 miles) in radius orbiting within the Encke gap in the A ring. An entourage of tiny objects may surround the F ring, sporadically "tweaking" the orbits of its particles into their stranded,

kinked appearance.

Objects this small are susceptible to destruction by meteoroids. The risk of such destruction increases with proximity to a giant planet, because its strong gravitational field accelerates approaching meteoroids, multiplying their force of impact. The great destructive power of meteoroids that get close to the giant planets may help explain why, around all the gas giants visited so far by the *Voyagers,* we find more numerous but smaller satellites and, as we look nearer the planet, ring systems. It appears that satellites unlucky enough to orbit close to the planet are much more likely to be dealt a shattering blow.

Before *Voyager*, we assumed that Saturn's rings were as old as Saturn, but the apparently youthful features seen in all known planetary ring systems now point toward recent creation of rings—possibly by destruction of moonlets.

To produce Saturn's main rings, a moon the size of Mimas would have to be pulverized, an event of low probability since it would require a colliding projectile of several kilometers' radius. However, the uranian rings and Saturn's stranded F ring each contain only the mass of a moonlet with a radius of 1 kilometer (0.6 mile).

It may be that many rings, like us, are temporary residents of the solar system. A planetary ring that we see today may be only one of a succession of features that spring into existence and then vanish many times over during the lifetime of the Sun.

It is surely no accident that the ring arcs around Neptune lie in the same region of transition from rings to moons that we have seen around the other gas giants. Most likely Neptune's ring arcs will be found to mingle with their own population of "ringmoons." The arcs may be nothing more than transient clumps of debris created by meteoroid destruction of ringmoons. Further insight along these lines is clearly one of the main goals of the Neptune encounter.

Titan: Recipe for Life?

Most scientists believe that life is a product of a long chemical chain that has its beginning in oceans or atmospheres abundant in nonliving organic material ("organic" in chemistry means "containing carbon"). Complex organic molecules are not unique to Earth; amino acids have been found even in primitive meteorites. In a classic laboratory experiment, Stanley Miller and Harold Urey showed that an atmosphere containing only simple gases like methane (CH_4), ammonia (NH_3) and water (H_2O), and energized by electrical discharge, can yield complex organic material such as amino acids and other building blocks of life. Gigantic Titan presents just such an environment in its atmosphere and on its surface.

Titan's surface is completely obscured by a thick haze of organic aerosol particles, produced in its nitrogen-methane atmosphere by an alchemy of ultraviolet light, magnetospheric protons and electrons, and cosmic rays. Before *Voyager*, the depth of its atmosphere was unknown; one of the most suspenseful periods of the *Voyager 1* Saturn encounter came as the spacecraft flew behind Titan with its radio transmissions slicing through the thick atmosphere. It was touch and go whether any surface would be detected before the beam faded into the noise, but detected it was—more than 350 kilometers (220 miles) below the topmost layer of haze.

We found a surface pressure 60 percent greater than on Earth. Subtle inflections in the intensity of the weakening radio beam suggest that there may be thick rain clouds of methane at some places in the dense atmosphere. The *Voyager* infrared spectrometer detected a pharmacopeia of organic molecules in Titan's atmosphere—from simple hydrocarbons like ethane (C_2H_6), acetylene (C_2H_2) and propane (C_3H_8) to more complex compounds containing nitrogen, such as hydrogen cyanide (HCN), cyanoacetylene (HC_3N) and cyanogen (C_2N_2). Organic chemists have long known that the chemical pathway that leads from simple atoms like hydrogen, nitrogen and carbon to the complex molecules from which our cells and genetic material are made gets started with these very compounds. This pathway would be rapidly short-circuited in the hydrogen-rich atmospheres of the gas planets, but in Titan's nitrogen-methane atmosphere, no one knows how far the path may lead.

Major advances in our understanding of this giant organics factory have continued in the years since encounter. In 1983, we realized that the ethane produced in Titan's atmosphere must be liquid at Titan's surface temperature and pressure. Furthermore, the amount produced over the age of the solar system is large enough that much of the surface of Titan could be covered with an ocean of liquid hydrocarbons hundreds of meters to tens of kilometers deep. Such an ocean, containing the floating, sunken or dissolved residues of more complex carbon-nitrogen-hydrogen compounds, would be a playground of organic chemistry like none other in our solar system.

A Chance to Go Again

We have discovered dynamism not only in the turbulent atmospheres of the gas giants but in their ring-moon systems as well. The Saturn system is especially well endowed with dynamic phenomena, and our understanding continues to increase steadily almost a decade after the initial encounter.

Yet fundamental questions remain that have no answer in the *Voyager* data set. NASA, in cooperation with the European Space Agency, has recently proposed to initiate the *Cassini* mission to Saturn, consisting of a Saturn orbiter and a Titan atmospheric probe. If *Cassini* and its sister mission CRAF (Comet Rendezvous Asteroid Flyby) are approved by Congress this year, we and future generations will continue to receive the rewards and insights of planetary exploration into the next century.

Jeff Cuzzi, Research Scientist at NASA's Ames Research Center, is a member of the Voyager *imaging team.*

URANUS: BENEATH THAT BLAND

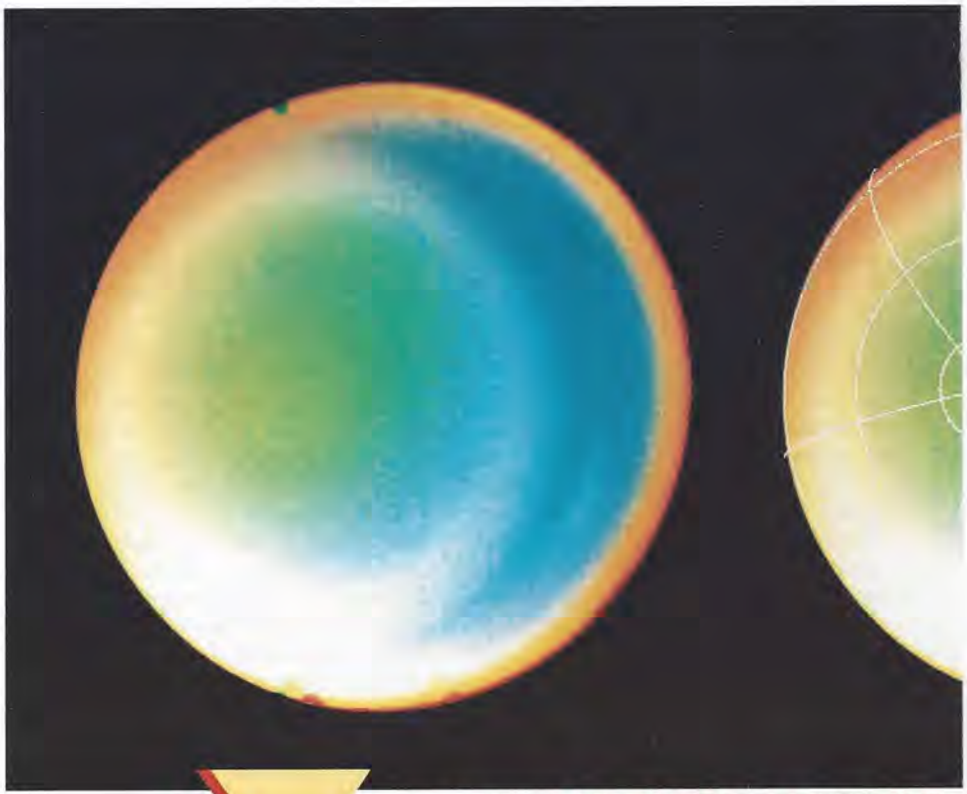
Voyager 2's third destination on its Grand Tour was the Sun's seventh planet, Uranus. On January 24, 1986, the spacecraft flew within 82,000 kilometers (51,000 miles) of the planet. This was Uranus' first visitor from Earth.

As at Jupiter and Saturn, we discovered much about the planet, its magnetic and radiation fields, its rings and its satellites. Uranus' almost featureless face betrayed few secrets to the spacecraft's cameras, and the thin, extremely dark rings were difficult to image. To penetrate the planet's mysteries required the best efforts of all team members working on *Voyager 2*'s instruments. The radio science investigation in particular became a major contributor to our knowledge of the uranian system.

The radio team used the regular communications link with Earth in several ingenious ways. The extreme stability of the radio's frequency permits *Voyager* navigators to measure the spacecraft's speed to within millimeters per second. By measuring variation in speed resulting from tiny tugs from the planet and its satellites, they could measure the gravitational fields and so derive the masses of the bodies.

As the spacecraft passed behind the planet (and was occulted, or hidden, as seen from Earth), the radio signal passed through Uranus' ionosphere and atmosphere. Just as light passing through water is slowed and bent, so the radio signal changed, enabling scientists to discern structure in the ionosphere and atmosphere, and construct a temperature and pressure profile of this strange world.

Voyager 2's trajectory was carefully chosen so that the radio beam would also pass through the tenuous ring system. Changes in the signal's amplitude and phase told scientists much about the amount of matter in the rings and the size of their component particles.



The face of Uranus was the least detailed on any world visited by Voya
features in images of the planet, scientists were forced to resort to he
false-color techniques. In the image to the right, researchers have ove
treme tilt and to show that faint atmospheric features correspond to t
However, the radio experiment, using the spacecraft's communication
atmosphere and taught us much about the atmosphere and clouds of

Atmosphere

After the kaleidoscopic storms of Jupiter and the butterscotch banding of Saturn, the blue-green disk of Uranus seemed rather bland. Uranus' atmospheric patterns proved very difficult to decipher. *Voyager 2*'s cameras followed several cloud features long enough to derive wind speeds. Seven of the eight appeared in the mid-latitudes, moving in the same direction as the planet rotates, between 50 and 150 meters per second (110 to 330 miles per hour). The eighth cloud, closer to the south polar region, moved even faster, near 190 meters per second (420 miles per hour).

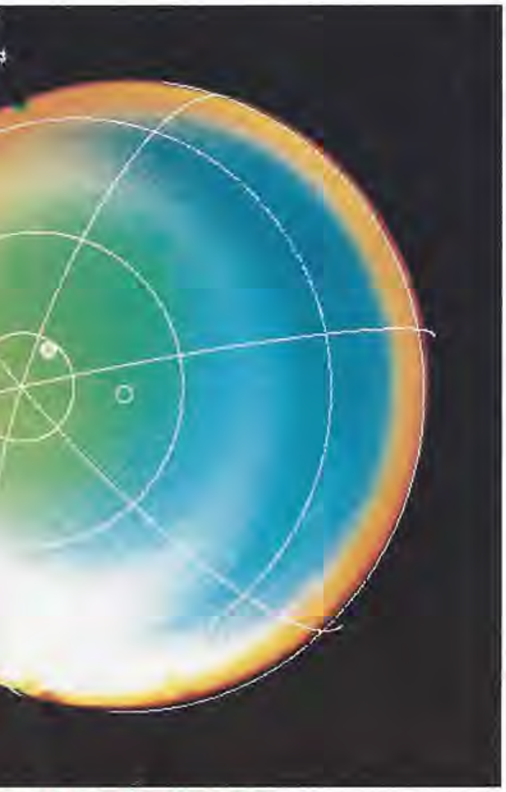
The radio science results showed that the atmosphere at the equator rotates 110 meters per second slower than the planet rotates; winds reverse direction as they approach the equator. This wind profile indicates that Uranus' atmospheric gases rise near the poles and sink near the equator. (This is in contrast with Earth, a very different planet, where air rises near the equator and then sinks at mid-latitudes, causing the jet stream.)

Voyager 2's instruments carefully measured the planet's temperature and the amount of sunlight it absorbs. Analysis showed that little or no internal heat escapes from Uranus, whereas its larger cousins Jupiter and Saturn still glow with heat left over from their formation. Scientists on the infrared interferometer spectrometer team concluded that less than 13 percent—and perhaps none—of Uranus' heat is generated in the interior. Since escaping heat drives atmospheric turbulence, this lack of heat may partly explain the planet's bland appearance. It's also possible that extensive layering within Uranus' deep atmosphere acts as insulation, inhibiting the release of heat. If so, the interior may have cooled very little since its formation.

The bland blue face of Uranus seen in *Voyager 2* images of the planet rep-

EXTERIOR

by Richard A. Simpson and Ellis D. Miner



ger. To discern any atmospheric
pic contrast-enhancement and
laid a grid to show Uranus' ex-
e planet's rotation about its axis.
s beam, was able to penetrate the
Jranus. *Image: JPL/NASA*

resents only the topmost layer of clouds. The atmospheric depths were hidden from view. The radio occultation experiment, which sliced through the atmosphere as *Voyager 2* passed behind the planet, covered a narrow region near the equator and penetrated about 250 kilometers (150 miles) into the atmosphere. Even at this depth, we were still seeing only the outermost skin of Uranus.

To determine Uranus' equatorial radius, scientists watched as *Voyager 2* disappeared behind the planet and reappeared on the other side. Then they measured the distance between the two points. Determining these two points, however, required an arbitrary choice since Uranus, a gas planet, does not offer an obvious edge from which to measure. On gas giants, which have very tiny solid cores, if any at all, the surface is sometimes considered to be the level of the atmosphere where the pressure equals one bar (a unit equal to the pressure of Earth's atmosphere at sea level). On Uranus, the distance between one-bar readings at the equator gives a radius of about 25,559 kilometers (15,882 miles). Using data from the spacecraft and from Earth-based observations, the radio scientists extrapolated that the radius from Uranus' center to its poles is about 24,973 kilometers (15,517 miles). Thus Uranus, like Earth, is slightly squashed at the poles (because of rotation).

The radio team identified a minimum temperature of about –220 degrees Celsius (–360 degrees Fahrenheit) at the 100 millibar level of the atmosphere. The temperature increases with depth to about –172 degrees Celsius at the 2.3 bar depth and increases with altitude to about –160 degrees at 0.5 millibar.

The radio science and infrared instruments determined that the atmosphere above the obscuring blue clouds is about 85 percent hydrogen with the rest mostly helium. The other gas giant planets, as well as the Sun, are similar mixtures of these two most abundant elements in the universe.

The radio scientists saw a dramatic change in the radio signal at the 1.2 bar level of the atmosphere, representing a methane cloud layer some two to four kilometers thick. These clouds are the products of the temperature and pressure conditions at the 1.2 bar level in Uranus' atmosphere, just as water vapor in Earth's atmosphere condenses into clouds at certain levels. Below the cloud layer, methane may represent as much as 2.3 percent of the uranian atmosphere; above the clouds the concentration is far less.

At greater altitudes, the ultraviolet spectrometer measured a very extended layer of hydrogen with temperatures up to 525 degrees Celsius (980 degrees Fahrenheit). The radio science team also found evidence of an extended ionosphere (an atmospheric layer characterized by charged particles) that may be related to this "exosphere" of hydrogen. The hydrogen interacts with sunlight so that the illuminated atmosphere glows with ultraviolet light. The process that generates this "electroglow" is still a topic of lively debate.

Magnetic Field

For 37 days, beginning 5 days before *Voyager 2* reached Uranus, the planetary radio astronomy investigation monitored radio signals generated by interactions between charged particles and the magnetic field. By tracking these signals, we learned that the planet rotates on its axis every 17.24 hours. The magnetometer investigation verified this period. It also found that the the magnetic field is tilted 58.5 degrees from the rotation axis, and offset from the center of the planet by nearly 8,000 kilometers (5,000 miles).

This highly tilted and offset magnetic field is the strangest among planets yet visited by spacecraft. Uranus' rotation, tilt and interaction with the solar wind combine to produce a corkscrew-like structure trailing out behind the planet. The solar wind, a stream of charged particles thrown off by the Sun, blows most planets' magnetospheres into a teardrop shape.

The offset from the planet's center causes magnetic-field strengths at Uranus' one-bar "surface" to vary by a factor of ten between the north and south magnetic poles. Trapped within this wobbling magnetic field is an intense radiation field, which consists almost exclusively of electrons and protons. The source of these particles is probably the hydrogen exosphere seen by the ultraviolet investigation.

Rings

In 1977, James Elliot of MIT (then at Cornell) and his colleagues discovered the uranian rings when they noticed that the light from a star blinked several times just before the planet occulted it. Similar Earth-based occultation observations disclosed most of the rings' dimensions before *Voyager 2*'s closest approach, but we still had much to learn about these narrow and perhaps temporary structures.

With its photopolarimeter, imaging, ultraviolet and radio science instruments, *Voyager 2* refined the telescopic measurements and made the first detailed images of the rings. It also discovered two new rings.

Since colors are a clue to the compositions and histories of solar system objects, it was very important to examine them in visible light. As the spacecraft passed through the planet's shadow, the *Voyager 2* cameras glanced back at the rings to see them in the "forward-scat-

At only 480 kilometers (300 miles) in diameter, Miranda is the smallest of Uranus' five major satellites, but what it lacks in size it makes up in strangeness. The face of this little moon displayed the most varied terrain **Voyager 2** ***has yet seen in its reconnaissance of the outer solar system, with fault valleys, parallel ridges, impact craters and strange ovoid features unique to Miranda. The top image is a photomosaic of*** **Voyager** ***images; the bottom is a map made from those images.***

Map: US Geological Survey, Flagstaff

tered" light that reveals fine material. The cameras found a tenuous sheet of dust spanning the entire ring system.

Uranus' rings are extremely dark, reflecting only about 5 percent of the sunlight falling on them. Like Saturn's glimmering ring system, the uranian rings are probably made up of water ice particles, but this usually bright material may be contaminated by methane (CH_4). The energetic exosphere discovered by *Voyager 2* could strip the hydrogen from the methane, leaving behind a dark carbon coating on the ring particles.

As the radio beam passed through each of the nine rings known before encounter, it created profiles of their optical depth (this is a measure of the light-intercepting capacity of a cloud of material, and so gives an indication of the properties of the particles). Uranus' rings are extremely narrow, typically less than 10 kilometers across, whereas Saturn's system is thousands of kilometers in width. The spacecraft was nevertheless able to pick out rich structural detail. Several instruments picked up tenuous companions to the eta and delta rings. The imaging and photopolarimeter systems reported additional rings that did not show up in the radio science data, most probably because the particles there are much smaller than the radio wavelength.

The combined results indicate that, unlike the saturnian and jovian rings, the uranian system contains surprisingly few particles smaller than fist-sized. We would expect such small particles to be created as icy ring particles collide, perhaps to re-accrete later into larger particles. This is what we would expect in a system that had reached collisional equilibrium, which seems to be what we saw at Jupiter and Saturn.

So what's happening to the dust at Uranus? The bloated hydrogen exosphere may be sweeping the rings clean of dust, while the rings erode before our eyes. *Voyager 2* may be telling us that planetary rings are relatively transient phenomena.

The plasma wave investigation recorded the effects of micron-sized particles striking the spacecraft as it crossed the ring plane of Uranus. The team estimated the cloud of fine particles to be about 3,500 kilometers (2,200 miles) thick with a maximum concentration of 1.6 particles in each 1,000 cubic meters. Such a low-density cloud would be invisible to other investigations, and the spacecraft suffered no perceptible damage.

Satellites

Voyager 2 discovered 10 new satellites, all orbiting inside the 5 previously known satellites. The imaging system was able to resolve the disks of 7 of the 15 moons; the others remain only points of light. All the new satellites are smaller and darker than the five "classical" satellites. As with the rings, this darkness may be due to the high-energy protons in Uranus' exosphere bombarding the methane ice on the satellite surfaces, releasing the hydrogen and leaving behind a carbon (organic) residue.

Voyager 2 moved through the uranian system at a relative velocity of over 14 kilometers per second (30,000 miles per hour), while the gravitational effects of the planet and satellites tugged on the spacecraft. The effects let us use tracking data, combined with imaging data and eight years of telescopic observations from Earth, to determine the masses of Uranus and its largest moons. The satellites seem to be made primarily of water ice and rock. The densest, Titania, is about 69 percent more dense than water; the lightest, Miranda, is 25 percent more dense than water. Earth is 450 percent more dense than water.

Detailed images of the five largest uranian satellites—Oberon, Titania, Umbriel, Ariel and Miranda—revealed a far greater diversity than scientists had anticipated. Their grooved and cracked surfaces suggest a higher level of tectonic activity than we would expect for such small, icy bodies. Tectonics is the movement in planetary crusts that is found on larger bodies—such as Earth—with some sort of internal heat to drive the motions. Many forces, some perhaps tidal, some impact, may have reworked the surfaces of the uranian satellites.

Titania, Ariel and Miranda are crisscrossed by surface fractures. Ice appears to have flowed across Ariel's surface. Miranda possesses three baffling "coronae" that may be results of partial melting of the interior during its youth. As satellites mature, the materials that comprise them can, under suitable conditions, differentiate and settle into denser, rocky cores with lighter, icy surfaces. If Miranda's coronae, each of which is nearly rectangular in shape and contains a series of concentric structures, are the result of ice flowing up to the surface, the process of differentiation must have been halted in midcourse. Or perhaps the coronae are the result of processes that we don't yet understand.

Voyager 2 taught us much about the motion, composition and origin of the objects that make up the uranian system. These data illustrate both similarities and differences among the giant planets of the outer solar system. After the Neptune encounter in August, our initial reconnaissance of these bodies will be complete. The results will provide substance for scientific discussion for decades to come.

Richard A. Simpson is an Associate Member of the Radio Science Team on the Voyager *Project. Ellis D. Miner is* Voyager's *Deputy Project Scientist at JPL.*

VOYAGER 2 APPROACHES NEPTUNE

by Ellis D. Miner

Excitement is building rapidly at Caltech's Jet Propulsion Laboratory as *Voyager 2* plummets toward its August 25 closest approach to the solar system's eighth planet. We're closing the gap at the rate of 1,450,000 kilometers (900,000 miles) per day. Images from *Voyager 2*'s high-resolution vidicon camera keep improving in detail (since late 1988 they have exceeded anything obtained from Earth). With all the pre-encounter tests of the spacecraft complete, the *Voyager* Project team at JPL is rehearsed and ready. We will be handling a flood of new data during the four-month Neptune encounter period, from June 5 through October 2, 1989.

At its closest approach to Neptune, *Voyager 2* will sail over the north polar regions of the planet only 29,200 kilometers (18,100 miles) from the planet's center, a scant 5,000 kilometers (3,100 miles) from its polar cloud tops. The moment of closest approach will actually occur on August 24 at 9 p.m. Pacific Daylight Time (PDT), but the radio signals from *Voyager 2*, traversing the 4.5 billion kilometers (2.8 billion miles) to tracking stations near Canberra and Parkes, Australia, and Usuda, Japan, will be received at 1:06 a.m. PDT on August 25. *Voyager 2*'s passage behind the planet will be monitored by those stations from 1:12 a.m. through 2:01 a.m. PDT.

A short 5 hours, 14 minutes after "Neptune closest approach," *Voyager 2* will fly within 40,000 kilometers (25,000 miles) of the center of the planet's largest moon, Triton, and just half an hour later will take four minutes or less to slice through the moon's shadow.

Only four days earlier, *Voyager 2* will have celebrated the 12th anniversary of its launch from Cape Canaveral. The spacecraft's twin, *Voyager 1*, was launched on a faster trajectory 16 days after *Voyager 2*. Both spacecraft have operated continuously since launch. Each is tracked for 8 to 16 hours a day during interplanetary cruise periods and 24 hours a day during planetary encounter periods.

Tuning Up the Equipment

Because Neptune is so much farther from the Sun and Earth than Uranus, light levels are lower and the received signal strength is weaker. These conditions have made it necessary to modify the spacecraft as well as the receiving antennas on Earth. All three of NASA's 64-meter antennas (at Goldstone, California; near Canberra, Australia; and near Madrid, Spain) have been enlarged to 70-meter diameters and made more efficient. A high-efficiency 34-meter antenna has been added at Madrid so that each site now has one 70-meter antenna and two 34-meter antennas.

Non-NASA antennas will also track *Voyager 2* during the Neptune encounter. After taking part in the 1986 Uranus encounter, the Parkes (Australia) Radio Telescope will again assist the Canberra stations in data collection, and both Parkes and Usuda (Japan) will help collect radio science data as the spacecraft passes behind Neptune and Triton. The Very Large Array (VLA) near Socorro, New Mexico, will collect *Voyager 2* telemetry data with its twenty-seven 25-meter antennas and combine that signal via communications satellites with data collected by the Goldstone tracking array. VLA provides an additional tracking capability equivalent to one and a half 70-meter antennas.

Changes we've made to the spacecraft to accommodate lower light levels at Neptune include reprogramming *Voyager 2*'s computers to (1) allow longer imaging exposures, (2) steady the spacecraft and (3) provide new means of compensating for relative motions of the spacecraft and the target body. Typical exposures at Neptune will be 15 seconds or longer (whereas 5 seconds was typical at Uranus). The new capability permits exposures of up to 61 seconds, plus integer multiples of 48 seconds. Camera wobble has been slowed from 1/10th the angular rate of the hour hand on a clock to 1/25th that rate. Image motion compensation can now be done by nodding the spacecraft to match target motion during an exposure without turning far enough to interrupt the flow of data back to Earth. During the Uranus encounter, we compared the challenge of *Voyager 2*'s photography to taking a picture of a piece of coal against a black background at twilight. At Neptune, the lighting is about half as good.

What to Look For

To appreciate how far away it really is, consider that Neptune has not completed an orbit around the Sun since its discovery in 1846. Distance makes Neptune a very difficult object to learn much about. We know its orbital period is 165 years, but its rate of rotation is still uncertain. Recent studies have yielded rotation periods from 17 to 18 hours, but these times are based on the motions of clouds across the disk and may not represent the rotation period of Neptune's interior.

Magnetic and radiation fields undoubtedly surround the planet, but we don't know their strength and extent. There may also be a rudimentary ring system, possibly consisting of a few elongated and relatively isolated collections of debris, created by collisions of small satellites that we have not yet discovered. These or other satellites may also prevent the ring material from spreading and dissipating, either along the ring or toward the planet.

Two teams of observers in Arizona may have detected such a satellite as it briefly blocked the light of a star in May 1981. Searches for undiscovered satellites will be a prime objective of *Voyager 2*.

Triton, Nereid and 1989N1 are the known satellites of Neptune. Triton is the only major moon in the solar system to travel in a retrograde (backwards) orbit around its planet. Four of Jupiter's tiny outer moons are retrograde, and Saturn's little Phoebe is retrograde; these five moons, however, are believed to be captured asteroids. With a diameter of 2,800 to 3,600 kilometers (1,700 to 2,200 miles), Triton is much too large to be an asteroid. It travels around Neptune in just under six days along an orbit inclined 21 degrees from Neptune's equator. Its orbit is nearly circular at an average distance of about 354,000 kilometers (220,000 miles) from the center of the planet.

Telescopic measurements show that Triton has methane ice on its surface. Temperatures at the surface may be near 50 degrees kelvin (–370 degrees Fahrenheit), close to the condensation temperature of nitrogen, and some scientists have speculated that condensed nitrogen (probably solid) may exist on the surface, perhaps forming frozen lakes. Even without the nitrogen, Triton's methane would cause a thin atmosphere to form; if nitrogen is present, Triton might have an atmosphere more substantial than that of Mars.

Nereid's orbit is inclined 28 degrees to Neptune's equator and is extremely elongated. Nereid's distance from Neptune ranges during a single 359-day orbit from a minimum of about 1.4 million kilometers (870,000 miles) to a maximum of 9.5 million kilometers (5.9 million miles). Its diameter is thought to be between 300 and 1,100 kilometers (200 and 700 miles).

Above: Neptune and its large moon Triton are the last ports of call on* Voyager 2*'s Grand Tour.

Painting: Michael Carroll

Right Background: Even while* Voyager 2 *was still 134 million kilometers (83 million miles) away from Neptune, it was already picking out detail in the atmosphere. These five views show how the planet looked through five of the filters on the spacecraft's narrow-angle camera.

Image: JPL/NASA

The diameter of 1989N1 is somewhat smaller; it occupies a prograde, circular orbit about 117,500 kilometers (72,800) miles) from Neptune's center.

The Agenda of Measurements

Atmosphere. Images obtained before the encounter period reveal banded structure and discrete clouds, and thus Neptune will not emulate the bland appearance of Uranus. Encounter measurements of the atmosphere began June 5 with color imaging every 3.6 hours until mid-August, when the planet will no longer fit in a single high-resolution frame.

Infrared temperature and composition measurements begin on August 16. Then, during the period from seven days before until seven days after Neptune closest approach, *Voyager 2* will map the planet and take higher-resolution images of selected atmospheric features. During the closest 48 hours, infrared, imaging and photopolarimeter instruments will record variations in brightness at different times of day (and thus in changing levels of sunlight). These observations, when combined with infrared temperature readings, will provide a measure of heat flowing from the interior of Neptune.

The most definitive measurements of the deep atmosphere near and below the cloud tops will come from radio waves transmitted through the atmosphere by the spacecraft as it passes "behind" the planet as viewed from Earth. These data will provide a profile of the atmosphere's structure and composition. These data will help to provide measurements of helium and methane abundance, the variations of temperature and pressure with depth, and the vertical locations of cloud and haze layers.

Magnetic and Radiation Fields. Six of *Voyager 2*'s eleven scientific investigations will assay the solar wind/planetary magnetosphere environment, measuring charged particles, plasmas,

Above and Left: With its substantial atmosphere, Neptune's large satellite Triton is ripe with possibilities. Some scientists have concluded that lakes of liquid nitrogen may lie on its surface. Others say such lakes, if they exist, must be frozen. We will not know exactly what this moon will look like until* Voyager 2 *flies past in August, but some artists have already visited Triton in their imaginations. Here are two artists' versions of what this moon might look like.

Top painting: MariLynn Flynn
Left painting: Michael Carroll

magnetic fields and the lower-frequency radio waves generated by their interactions. Periodic radio emissions will likely be the best indicators of Neptune's internal rotation period, as they have been at Jupiter, Saturn and Uranus.

Voyager 2 is expected to travel within the magnetic field of Neptune from August 24 until August 28. The passage of *Voyager 2* over Neptune's north polar region may give us our first opportunity to measure directly the polar magnetic and radiation fields of one of the solar system's four giant gaseous planets.

Ring Material. Neptune's ring arcs, if they exist, bear little resemblance to the ring systems seen at Jupiter, Saturn and Uranus. *Voyager 2* will search for ring material in orbit around Neptune. If any ring arcs are discovered a week or more before closest approach, then remote-sensing instruments will be trained on them to make high-resolution mosaics and measure blockage of starlight, sunlight and spacecraft radio beams. The plasma wave instrument will also "listen" for evidence of tiny ring particles striking the spacecraft during the inbound and the outbound crossings of Neptune's equatorial plane.

Nereid. Because of the long loop of Nereid's orbit, *Voyager 2* won't get closer to that moon than 4.6 million kilometers (2.9 million miles). At that range, high-resolution images will show features as small as 90 kilometers (60 miles). While we won't be able to resolve individual craters, regional brightness differences should be apparent, and we can compare them with earlier imaging sequences to determine Nereid's rotation rate. The unusual orbital characteristics militate against synchronous rotation, in which a satellite keeps the same face toward the planet it orbits.

Triton. A fitting climax to *Voyager 2*'s Grand Tour of the Outer Planets may well be the encounter with Triton. Here is a satellite large enough to hold an easily detectable atmosphere but not so large that the atmosphere is likely to obscure the surface (as was the case for Saturn's Titan). Triton will be scrutinized by the optical instruments for an entire six-day orbital period. High-resolution studies begin with a full-color, full-disk image just two hours before Neptune closest approach.

For an eight-hour period, beginning two hours after Neptune closest approach, Triton will be the sole target of *Voyager 2*'s remote-sensing instruments. Moderate-resolution color mapping will be followed by higher-resolution, non-color mapping. After an infrared atmospheric study, *Voyager 2* will perform highest-resolution imaging along with ultraviolet, infrared and photopolarimeter coverage, revealing features smaller than one kilometer. This eight-hour period may also provide the best measurements of Triton's mass (and hence its density), as calculated from the moon's effect on *Voyager 2*'s flight path.

The ultraviolet and photopolarimeter instruments will then aim beyond the horizon at a star to detect any atmosphere-caused variations in the star's brightness. Further investigations of Triton's atmosphere by the ultraviolet and radio science instruments will span the period when *Voyager 2* passes through Triton's shadow. Studies of its crescent phase and dark side will occupy the remainder of the Triton close approach period.

The remainder of the Neptune encounter period is occupied with continued studies of Neptune's and Triton's dark sides and of Neptune's magnetic tail. Final calibrations for most of the instruments will also be performed prior to the official end of the encounter period on October 2. Data analysis and publication will likely continue for years to come.

As one who has had the pleasure of being intimately involved in *Voyager* science planning, data collection and publication of results since the 1977 launches, the author here thanks members of The Planetary Society, the United States Congress, the National Aeronautics and Space Administration and others who have been instrumental in advocating, supporting and applauding the *Voyager 2* adventure. For centuries to come it will stand as one of humankind's great explorations.

Ellis Miner is Voyager*'s Deputy Project Scientist at JPL. He was previously involved in the* Mariner 6, 7, 9 *and* 10 *and* Viking *missions.*

World Watch

Views of Mars from *Phobos 2*

The Soviet *Phobos* mission to the planet Mars and its largest moon ended abruptly on March 27, 1989. But before the spacecraft was lost, it managed to return some fascinating and important data on the Red Planet. Some of the most spectacular results came from the Termoskan instrument, which examined the planet in the thermal-infrared part of the spectrum. In essence, it measured heat radiated from the surface.

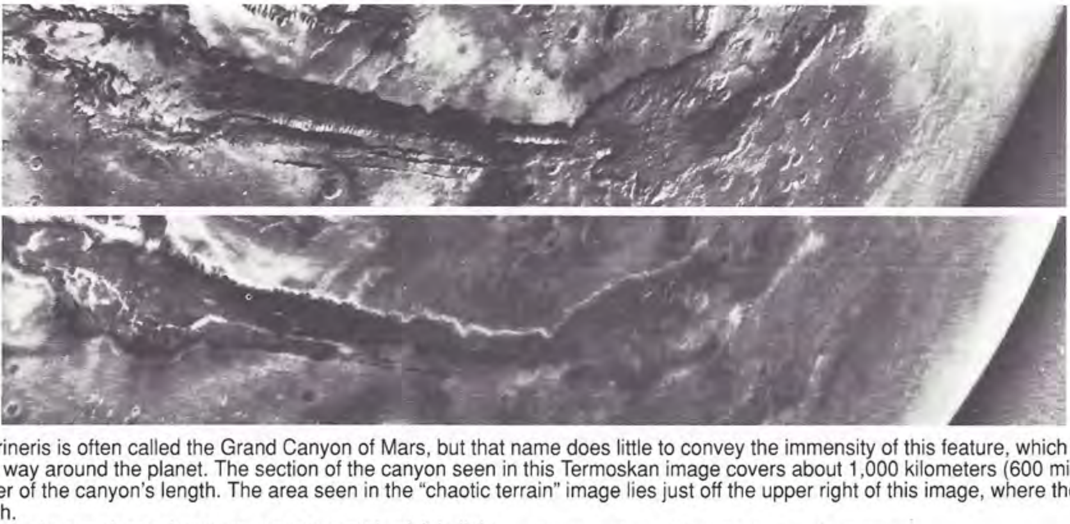
These Termoskan images reveal differences in temperature between areas on the planet surface. The areas that appear dark in these images have lower temperatures, but they are not necessarily dark to the eye. Conversely, light areas have higher temperatures. From information about temperature, scientists can infer other important details about the surface. For example, fine dust cools and warms more quickly than solid rock. During the day, dusty regions will be warmer, and therefore will appear brighter in the thermal-infrared spectral band seen by this instrument. At night, the opposite will be true: fine dust will appear darker and colder than solid rock.

Crater Schiaparelli

This image of the crater Schiaparelli was taken at noon. The dusty areas appear light and the coarser surface features are dark. This large crater, about 400 kilometers (250 miles) in diameter, was one of the first to be imaged by spacecraft from Earth when the *Mariner 4* flew by the planet in 1965.

Chaotic terrain

Chaotic terrain is one of the most intriguing types of surface features found on Mars. Some scientists believe that catastrophic floods may have formed such regions when water stored in subsurface aquifers was suddenly released. The chaotic terrain seen in this image connects the great canyon Valles Marineris (Mariner Valley) to Chryse Planitia (the Plain of Gold) where the *Viking 1* lander now sits.



Valles Marineris

Valles Marineris is often called the Grand Canyon of Mars, but that name does little to convey the immensity of this feature, which stretches one-fifth of the way around the planet. The section of the canyon seen in this Termoskan image covers about 1,000 kilometers (600 miles), or about one-quarter of the canyon's length. The area seen in the "chaotic terrain" image lies just off the upper right of this image, where the canyon turns to the north.

The bottom image shows the same area as seen in visible light.

Images courtesy of Margarita Naraeva, Glavkosmos

THE VOYAGER INTERSTELLAR MISSION

by Dan F. Finnerty

While all eyes have been focusing on the upcoming *Voyager 2* flyby of Neptune, *Voyager* Project members have been quietly considering new challenges for the veteran pair of spacecraft. Mission managers are planning to operate these spacecraft well into the next century—by which time they will have left the planets of the solar system far behind—in the *Voyager* Interstellar Mission (VIM).

Just how long are the *Voyagers* likely to survive, and what are they likely to find along the way? How will logistics change when *Voyager* is no longer a priority mission? These are questions that mission planners are seeking to answer on the eve of the last *Voyager* planetary encounter.

How Far Can Voyager Go?

Just how long the *Voyager* spacecraft can continue to function depends on many things, one of the most important being the electrical power needed to operate the computers, radios and scientific instruments. When the power runs out, the spacecraft will cease functioning forever.

The strength of the signals radioed back to Earth is also critical. If the signals become too faint, ground tracking stations will be unable to decode and interpret the data that the *Voyagers* are sending. Equally important, there must be sufficient fuel for each spacecraft to fire its thrusters and keep its high-gain antenna pointed directly at Earth. If the antenna drifts off point, the signals will radiate uselessly into space.

Electrical power for the *Voyager* spacecraft comes from radioisotope thermoelectric generators (RTGs), which directly convert the heat from the radioactive decay of plutonium into electricity. As the plutonium decays, less and less remains to provide heat, so the *Voyagers'* "batteries" are steadily running down.

Current predictions hold that the RTGs can power basic spacecraft operation until about 2025. Full instrument operations should be possible through 2000, and all fields and particles instruments should be operable through about 2015.

The strength of the radio signals transmitted back to Earth depends on several factors. Most important is the distance to Earth, which of course increases as the two spacecraft follow their separate paths into interstellar space. We can build larger tracking stations to acquire the ever fainter signals, or we can simply instruct the *Voyagers* to send data back more slowly. At the slowest rate of transmission for science data (about 43 bits per second), the *Voyagers* can likely be tracked until 2015 by stations with 34-meter antennas, and possibly, if either spacecraft still has electrical power, beyond 2030 by 70-meter tracking stations.

The *Voyager* spacecraft carry hydrazine fuel for use in two kinds of maneuvers: adjusting trajectory for planetary flybys, and maintaining attitude control so that the antenna points toward Earth. In the VIM era, there will be no need to make further trajectory corrections; hence all remaining fuel will be available for attitude control. If we adopt a conservative attitude-control strategy—using precision antenna-pointing only when absolutely necessary—the hydrazine should last until about 2025, and possibly longer.

End of Mission

As the *Voyagers* go farther from Earth, they also go farther from the Sun, which they use as a reference for antenna pointing. When the spacecraft can no longer track the Sun, they will drift away from Earth-point, eventually tumbling out of control. Analysis of the Sun-sensing equipment indicates that the *Voyagers* will probably be able to recognize the Sun until about 2030.

None of these projections takes into account the possibility of component failures. For the most part, each major spacecraft subsystem is backed up by a redundant system, and the *Voyagers* have enough onboard autonomy to take corrective action in the event of failures. However, there have already been several critical equipment failures that limit the ability of the spacecraft to survive.

Voyager 2 lost its primary command receiver shortly after launch and has been operating on its backup receiver ever since. If that should fail, it would be unable to receive further operating instructions. Also, the primary radio amplifier tube has worn out, leaving no backup for that either. If the backup tube fails, *Voyager 2* will be unable to transmit science data, although engineering-only telemetry could still be transmitted.

Voyager 1 has suffered a failure of one of its flight data system memories. If the backup memory fails, the spacecraft will no longer be able to process data for transmission to Earth. It is impossible to assess when or whether a catastrophic failure would occur on either spacecraft. Barring such problems, the two *Voyagers* should function until at least 2015, and perhaps as long as 2025 or even 2030.

Science: Which Plugs to Pull

Mission planners have considered a range of options for the *Voyager* Interstellar Mission, from a minimal "keep alive" configuration to full operation of all instruments. To be scientifically useful, the mission should at least continue operation of the fields and particles instruments (magnetometer; cosmic ray, plasma, and low-energy charged-particle instruments; and the planetary radio astronomy and plasma wave receivers). These instruments, while continuing to sample the outer solar system environment, would search for the farthest reach of the Sun's magnetic field, and then, having crossed this "heliopause," would go on to analyze the interstellar wind (a stream of charged particles flowing out from the stars).

A valuable enhancement to this basic mission would be continued studies of active galaxies, active binary stars, and pulsars by the ultraviolet spectrometer. Ultraviolet wavelengths can't be observed from Earth because of the screening effects of the ozone layer, and no other spacecraft currently in operation possess the *Voyagers*' capability at far-UV wavelengths. Information obtained at these wavelengths is particularly valuable because the most energetic astronomical phenomena radiate most of their energy in the ultraviolet. Measurements in this portion of the electromagnetic spectrum would fundamentally influence models of such objects.

Several experiments will end during VIM, the most prominent being imaging. Proposed observations were, unfortunately, too difficult to perform within the limitations of the extended mission, too unlikely to succeed or too expensive. Similarly, the infrared interferometer and spectrometer, photopolarimeter, and radio science experiments had to be dropped. Terminating these experiments was a difficult decision to make, but it freed up significant resources for the remaining experiments.

The Solar Medium

The *Voyager* spacecraft have already returned much valuable data about the Sun. Since launch the fields and particles instruments have monitored the solar wind, which blows out from the Sun at 400 kilometers (250 miles) per second, and when solar flares erupt, the planetary radio astronomy receiver picks up intense radio bursts.

The plasma (PLS) and low-energy charged-particle (LECP) instruments directly measure the density, composition, energy and flow direction of high-speed streams of solar material injected into space. The magnetometer observes associated fluctuations in the local interplanetary magnetic field. Taken as a whole, *Voyager* observations provide fundamental information on the physics and dynamics of the Sun's magnetosphere, the extended region influenced by the Sun's magnetism.

The *Voyagers* may already be detecting evidence of the heliopause. The plasma wave instrument has on occasion picked up radio emissions that may be caused by the collision of the solar wind with the interstellar wind. Theorists suggest that near the collision, as the solar wind slows suddenly, the magnetic field flowing with it becomes compressed, generating strong electric currents. These currents then rapidly accelerate solar wind particles, generating the observed radio emissions. This "shock wave" interpretation is still somewhat speculative; observations continue in an attempt to determine the source of the signals. We can expect even more interesting results as the *Voyagers* get closer to the heliopause.

Beyond the Solar System

In another set of observations—this time by the cosmic ray instrument—the *Voyagers* have come in contact with intriguing particles of interstellar origin. The cosmic ray instrument measures very high energy particles (atomic nuclei traveling near the speed of light), which can originate from supernova explosions, galactic magnetic fields and other high-energy phenomena. If they are electrically charged, such particles are deflected by the Sun's magnetic field. Neutral particles, however, can directly penetrate the heliopause. Once inside the heliosphere, flowing at relatively low speeds of 25 kilometers (15 miles) per second, the neutral particles may become ionized and captured by the solar wind, which flings them back toward the heliopause. At the heliopause they are accelerated by processes similar to those thought to cause the "shock wave" signals detected by the plasma wave sensor. The interstellar particles rebound at about one-tenth the speed of light into the solar system, where they are being detected by the cosmic ray instruments. This scenario, too, awaits confirmation from further VIM data.

Neutral interstellar particles that flow into the solar system are called the "anomalous cosmic ray component" because of their lack of carbon, one of the most abundant elements in nature. Current thinking holds that this lack of carbon results from the ease with which interstellar carbon is ionized, acquiring an electrical charge, and then blocked by the Sun's magnetic field from entry into the solar system. In 1985 *Voyager* instruments made the first positive detection of this anomalous cosmic ray component, sensing both argon and —unexpectedly—carbon.

Voyager Project planners can guess when the *Voyager 2* spacecraft will pass certain "landmarks" such as the heliopause, which signals the edge of our Sun's sphere of magnetic influence, and the Oort Cloud of comets, which marks the end of the solar system. Gauging *Voyager 2*'s speed and direction, they can estimate when it might make its closest approach to distant stars. As centuries pass, *Voyager 2's* actual itinerary will be known only to the spacecraft itself—and to any life-forms that happen across it.

This timeline represents the guesses of the *Voyager* program planning office as to the probe's adventures among the stars.

YEAR

2000	**2012**	**8571**	**20319**	**20629**	**23274**
Enters the heliosheath, the boundary region of the Sun's heliosphere.	Crosses the heliopause into the interstellar medium.	Closest approach to Barnard's Star, which may have a planetary companion. *Voyager 2* passes within 4.03 light years of the star, when the spacecraft is 0.42 light years from the Sun.	Closest approach to Proxima Centauri, star nearest to our Sun. *Voyager 2* passes within 3.21 light years of the star, when the spacecraft is 1.00 light years from the Sun.	Closest approach to Alpha Centauri, destination of many science fiction imaginings. *Voyager 2* passes within 3.47 light years of the star, when the spacecraft is 1.02 light years from the Sun.	Closest approach to Lalande 21185. *Voyager 2* passes within 4.65 light years of the star, when the spacecraft is 1.15 light years from the Sun.

We saw these carbon particles—in addition to taking the most accurate measurements yet of interstellar hydrogen, helium, nitrogen, oxygen and neon—because 1985 was near a period of minimum solar activity, which made it easier for interstellar particles to penetrate the solar magnetosphere. Cosmic rays came in mainly along a plane extending from the solar equator, in the "neutral sheet" formed where the magnetic field lines from the Sun's north and south poles meet.

During the current solar cycle, which will reach its maximum in about 1992, the magnetic polarity of the Sun is reversed from the previous cycle, which peaked in 1981. What will happen at the neutral sheet? Scientists await *Voyager* readings of cosmic rays during the solar maximum with great curiosity.

Will the rejuvenated magnetic field block out these cosmic rays entirely? Or will they be detected from different directions? What phenomena will the other instruments measure? The instruments of the spacecraft will be tuning in to a wealth of new science.

A Short Segment from the Information Digitally Encoded on the Voyager Interstellar Record

This *Voyager* spacecraft was constructed by the United States of America. We are a community of 240 million human beings among the more than 4 billion who inhabit the planet Earth. We human beings are still divided into nation states, but these states are rapidly becoming a single global civilization.

We cast this message into the cosmos. It is likely to survive a billion years into our future, when our civilization is profoundly altered and the surface of the Earth may be vastly changed. Of the 200 million stars in the Milky Way galaxy, some—perhaps many—may have inhabited planets and spacefaring civilizations. If one such civilization intercepts *Voyager* and can understand these recorded contents, here is our message:

This is a present from a small distant world, a token of our sounds, our science, our images, our music, our thoughts and our feelings. We are attempting to survive our time so we may live into yours. We hope someday, having solved the problems we face, to join a community of galactic civilizations. This record represents our hope and our determination, and our good will in a vast and awesome universe.

JIMMY CARTER
President of the United States of America

The White House
June 16, 1977

Garrison Operations

Operating the *Voyager* spacecraft in the VIM era will differ greatly from current methods. The flight team will shrink from more than 200 people to about 40. The way commands are generated for the spacecraft will also change dramatically. Instead of command sequences custom crafted for each activity, a set of onboard "command blocks" will be stored and reused as often as needed. Use of command blocks, which can be activated by simple ground commands, will reduce the complexity of operating the spacecraft, though it will also limit the flexibility of observations. Overall, operating the *Voyagers* is going to be safer, easier and less expensive.

To maximize telecommunications capability at extreme distances, the flight data system will be completely reprogrammed. The memory space made available by shutting down cameras and other instruments will be used to enhance data processing for the remaining instruments. The new data modes have been designed to work well with 34-meter tracking stations, since the 70-meter stations will be taken up by the *Magellan, Galileo, Mars Observer* and other high-priority projects.

The full value of the *Voyager* mission will be realized only after decades of steady observation and careful analysis—I find it interesting, to say the least, that on my retirement date in 2017, the *Voyagers* may still be on the job. And while the *Voyager* Interstellar Mission will not offer the same drama as the planetary encounters, the scientific value of exploring the outer limits of the solar system and interstellar space will redouble the triumph of *Voyager*.

Dan F. Finnerty is Deputy Science Investigations Support Team Chief on the Voyager *Project.*

26262	**28635**	**129084**	**296036**	**442385**	**957963**
Voyager 2 enters the Oort Cloud, the sphere of comets orbiting the Sun, estimated to extend between 20,000 to 200,000 AU out. (An Astronomical Unit equals the mean distance from Earth to the Sun.)	*Voyager 2* leaves the Oort Cloud and so exits our solar system.	Closest approach to Ross 154. *Voyager 2* passes within 5.75 light years of the star, when the spacecraft is 6.39 light years from the Sun.	Closest approach to Sirius, brightest star visible from Earth. *Voyager 2* passes within 4.32 light years of the star, when the spacecraft is 14.64 light years from the Sun.	Closest approach to 44 Ophiuchi. *Voyager 2* passes within 6.72 light years of the star, when the spacecraft is 21.88 light years from the Sun.	Closest approach to DM+27 1311. *Voyager 2* passes within 6.62 light years of the star, when the spacecraft is 47.38 light years from the Sun.

News & Reviews

by Clark R. Chapman

The universe is incredibly vast. It is also intricately complex. We relate to our world on a "human scale," comparing things to a bread box or to a mile. Only with difficulty do we visualize our planet as a planet, yet Earth is small enough to fit inside Jupiter's Great Red Spot. Jupiter is puny compared with the Sun. But the Sun is miniscule compared with a red giant, like Betelgeuse in the shoulder of Orion. Interstellar distances, the galactic scale, clusters of galaxies, and so on—all beyond our ability to visualize. Or are they?

A few months ago, I had a chance to see a scale model of the universe. It is hard to believe that a museum exhibit could so successfully show the human scale, the scale of the universe and everything else in between. But a man named George Awad, a member of The Planetary Society's New Millennium Committee, has built a fantastic array of models that does just that. It is not located in any museum or planetarium, at least not yet. But it is open to the public, after a fashion. If you are in New York City, I suggest that you arrange to see it.

George Awad is president of a company that makes architectural models—scale models of skyscrapers and developments. But his hobby is astronomy, and he turned his craftspeople loose on an awe-inspiring project, to build a model of the universe. Needless to say, one scale model of the universe, even if it filled a great hall, could hardly show the details of anything as puny as our Milky Way galaxy, let alone the features of the solar system that are so relevant to us. So Awad adopted a scheme called "the powers of ten" that has been popularized in a couple of books and in an educational movie.

A group of school children visit George Awad's model of the universe.

Photograph: Courtesy of George Awad

Instead of building one model, Awad has built 75 models, each within a cube just a foot and a half per side, and each representing a linear dimension exactly 10 times that of its neighbor. The models are suspended overhead in a darkened gallery. As you walk from model to model, it's as though you had moved 10 times farther away each time. The display begins, simply enough, with a close-up of Carl Sagan's book *Cosmos* on the hood of a car. Moving to the next model, you see the whole parking lot, and the book is now tiny. In three more steps, you see the whole eastern coast of Florida, as if you had been launched in the shuttle a couple of minutes before. In three more steps there is a beautifully intricate model of the whole planet Earth; the book and the parking lot have long since been squeezed to the vanishing point.

Continuing from model to model, you then see the whole solar system, which thereafter shrinks to become an insignificant corner of our galaxy. We see the local group of galaxies, then larger clusters of galaxies, and super clusters, before finally reaching a somewhat fanciful representation of the entire visible universe. The effect is breathtaking because of the craftsmanship of the planetary models and the use of fiber optics to depict stars and galaxies.

George Awad is fascinated by the diversity of the universe, and he couldn't stick with just the geocentric perspective. At places, the model branches out to show other planets at the same scale as Earth, or other stars at the same scale as our Sun or the solar system. Altogether, there are 75 separate models hung in a rectangular array in the gallery. As a scientist, I was particularly struck by the extraordinary precision of the work. Every lunar crater is shown to correct scale, all the orbital inclinations have been measured properly, and the integrity of what we know about the cosmos has not been sacrificed to serve artistic ends, although the exhibit is exquisitely beautiful, indeed.

Awad has used his own resources to build this fabulous model. It is located in a mid-town building, not in a museum. Since Awad first unveiled his model a year ago, he has been in touch with various museums and planetariums around the country. There has been an expression of interest from the National Air and Space Museum, among others, but there are no firm plans for the exhibit to be shown outside New York City.

Meanwhile, it is possible for you to see this three-dimensional model of the universe through the powers of ten. George Awad is happy to arrange dates for public viewing at 260 West 36th Street. Just telephone Awad Astronomical Models in advance at (212) 563-5480. Although unheralded, this project is surely one of the major wonders to see in the Big Apple.

Clark R. Chapman is a member of the imaging team of the Galileo *mission, scheduled for an October launch toward Venus and Jupiter.*

SOCIETY Notes

CRAFOORD PRIZE

James Van Allen of the University of Iowa, a Planetary Society Advisor, has won the 1989 Crafoord Prize, which is awarded each year by the Royal Swedish Academy of Sciences in an area not covered by the Nobel Prize (astronomy is one such area).

Honored for three decades of research and leadership in magnetospheric physics, Van Allen is best known as the discoverer of the upper-atmospheric region called the Van Allen belts. The Academy cited him as a pioneer combining "superior expertise both in rocketry and in relevant scientific instrumentation."

Van Allen, who took part in *Explorer 1*, *Mariner 2*, and *Pioneer 10* and *11*, currently serves as an interdisciplinary scientist for the *Galileo* mission to Jupiter.

His response to the award was "one of humility, because my style has been to work with students and junior colleagues. One of my greatest pleasures has been to watch their evolution, development and achievement of leadership in this field."
—Charlene M. Anderson, Director of Publications

NATIONAL MERIT SCHOLARSHIP

Jennifer L. Avegno of Saint Mary's Dominican High School, New Orleans, has been named as the 1989 winner of a four-year National Merit Scholarship sponsored by The Planetary Society.

Each year this award goes to an outstanding high school senior planning to major in a field related to planetary science. Ms. Avegno, a student of remarkable accomplishment, is on her way to the University of Notre Dame to study aeronautics.
—Louis D. Friedman, Executive Director

NEW MILLENNIUM AWARDS

The New Millennium Committee Scholarship competition has also come to a close with final judging of student essays on the pros and cons of establishing a lunar base within the next 20 years. The winners are:

- Eric Engstrom of Chaminade College Preparatory School, West Hills, CA ($1,000)
- Amy Houts of Riverview High School, Sarasota, FL ($500)
- Edward Lux of Thomas S. Wootton High School, Rockville, MD ($250)
- Justin Tsai of West High School, Torrance, CA ($250).*—LDF*

COLLEGE FELLOWSHIPS

The Planetary Society has selected five promising undergraduates to receive $1,000 grants in support of their studies in a field related to planetary science. These winners earned distinction on the basis of academic achievement and a 2,500-word essay.

- David Baker, University of Texas, Austin, "The General Atmospheric Circulations of Earth and Venus"
- James Hugunin, Stanford University, "A Case for Manned Spaceflight"
- Charles Liu, Harvard University, "Recent Work on the Core-Instability Model of Giant Planet Formation"
- Andrea Schweitzer, Pomona College, "The Gravity-Assist Technique and Its Application to the Trajectory of *Voyager 2*"
- Adam Showman, Stanford University, "The Search for Extraterrestrial Life"

Congratulations to all the winners of fellowships and scholarships that are part of The Planetary Society's commitment to the future through education. All these students, and others pursuing studies that will one day guide us to the stars, deserve our encouragement.*—LDF*

SEDS INTERNATIONAL MEETING

Students for the Exploration and Development of Space will hold their 8th International Conference from August 24 to 28 in Pasadena, in conjunction with Planetfest '89.

Planetary Society Director Thomas O. Paine will deliver the keynote address, heading up an exciting program of panel discussions and student presentations, coverage of the *Voyager 2* encounter with Neptune and the Arthur C. Clarke Awards Banquet.

For registration information, write to Irwin Horowitz, SEDS Conference, 112-58 California Institute of Technology, Pasadena, CA 91125.*—Susan Lendroth, Manager of Events and Communications*

UNESCO COUPONS

In countries where foreign currency is scarce, Unesco Coupons generally offer the best rate of exchange and may be used as money for educational purchases, including membership in The Planetary Society.

For more information, write to: Unesco Coupons Programme, 7 Place de Fontenoy, F-75700 Paris, France. Or write to us for the address of the issuing agency nearest you.*—Iva Svitek, Assistant Manager, Data Processing*

CONTEST— 10TH ANNIVERSARY THEME

The 10th anniversary of The Planetary Society will be in 1990. While we celebrate our many accomplishments, we will also look toward the exciting possibilities of the coming decade.

As part of the celebration, we are sponsoring a special 10th Anniversary Theme contest. The winner will be recognized in *The Planetary Report* and will be awarded a trip to a 1990 anniversary event (locale to be determined).

Send your original motto or phrase that best sums up the essence of The Planetary Society of the future to: 10th Anniversary Theme, c/o The Society. Entries must be in by October 2.*—Tim Lynch, Director of Programs and Development*

KEEP IN TOUCH

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Pasadena, CA 91106

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Questions & Answers

Scientists have said that there is plenty of water under the ground on Mars. What solid evidence do we have to support such a claim?
—Ponniah Sivanesan, Danville, Illinois

There is strong geologic evidence that water exists underneath much of the martian surface. Water in this form is often called "ground ice." Some regions on Mars (the "chaotic" and "fretted" terrain) appear as if they were formed by the melting of underground ice. Several large channels on Mars, which we believe to have formed by catastrophic flooding, flow out of such regions. These areas are lower than their surroundings and have complex, hummocky floors, indicating some kind of collapse. Such a collapse could take place after the ground ice melted and flowed away.

The surface of Mars contains many unusual craters (rampart craters) that we have not seen anywhere else in the solar system. These craters are surrounded by lobes of material that extend outward from the crater like petals around the center of a flower. We think that these lobes were formed by material that "flowed out" from the crater when it was created by a crashing comet or meteorite. Such fluid behavior suggests that the crater was formed in ice-rich rock or soil, which would have become mud when heated by the impact.

Mars also contains surface features consistent with the creep of ice. Cliffs on Mars (like cliffs on Earth) commonly have piles of debris at their bases. However, the debris piles associated with many martian cliffs have forms that suggest they have undergone slow deformation and flow. Their appearance is much like that of rock glaciers on Earth, which are large tongues of ice and rock that creep slowly down slopes. The ice acts as a lubricant, allowing rock particles to slide past one another, resulting in slow movement like that of a fluid. This suggests that the material making up the cliff debris on Mars (which comes from the cliffs themselves) contains a significant amount of ice.

A similar process may be responsible for "terrain softening" on Mars. Craters in equatorial regions on Mars appear

The face of Mars displays a type of crater seen nowhere else in the solar system. Flows of ejected material form "splosh" features around the crater, suggesting that heat generated by a comet or meteorite's impact melted ground ice, and the resulting conglomeration of water and rock oozed out in flower-petal patterns. Image: JPL/NASA very "crisp" with sharp crater rims and steep slopes. By contrast, the appearance of the "softened" craters in nonequatorial regions can be explained by the presence of ground ice. The ice allows the underground material to move slowly and to flow to a more subdued shape. This relaxation slowly modifies the sharp rims of craters until they become rounded. Because we see sharp, pristine craters close to the martian equator and modified craters far from the equator, ground ice may exist close to the surface in regions where temperatures are colder.

The *Mars Observer* is scheduled for launch in 1992. This orbiting spacecraft will carry along a gamma-ray spectrometer that can detect water ice to a depth of one meter (3 feet) or so in the martian surface. This will be our first attempt to directly detect ground ice on Mars.
—DAVID G. JANKOWSKI, *Cornell University*

An asteroid crossed Earth's orbit on March 23rd but was not discovered until March 31. With all our advanced technology, how did we miss it? Will it return regularly like Halley's Comet?
—Natalie Pope, Burbank, Illinois

The close pass of asteroid 1989 FC by our planet on March 23rd was newsworthy because no other asteroid has been seen to come as close (less than twice the distance to the Moon). But it was hardly a remarkable event in the cosmic scheme of things. Dead comets and asteroid fragments are numerous and they are not easy to discover. For example, it has been estimated that there are probably about 1,000 objects larger than a kilometer (0.6 mile) in diameter whose orbits cross Earth's orbit. But only several dozen of them have been discovered so far. Patient observers using Schmidt camera telescopes continue to search the skies.

Henry Holt, who works in the search project led by Gene Shoemaker, discovered 1989 FC from the Mount Palomar Observatory about a week after its closest approach when it was rapidly zooming away. That was good fortune—it might have been missed altogether, and nearly was. Eleanor Helin, whose observing program has been supported in the past by The Planetary Society, was the next to observe 1989 FC, in early April. Nevertheless, the asteroid's orbit was difficult to calculate from so few observations, and 1989 FC was in danger of being lost forever. Because of interest, like yours, about when it will be back and whether or not it might hit Earth, astronomers worked hard during the last nights in April to photograph its much dimmer image.

They were successful, so we will be able to find it next spring, when it comes around again. Fortunately, it will not present a hazard on the next pass. Closer passes are possible in future decades, however, so astronomers will be trying to improve the orbital calculations. It is important to do so because 1989 FC measures at least 200 by 500 meters (600 by 1,600 feet). According to the final chapter in the new book, *Cosmic Catastrophes*, which I wrote with David Morrison, the impact of such an object would have devastating consequences, possibly even threatening the viability of civilization. That is all the more reason to strive to discover and catalogue the thousands of as-yet-undiscovered objects like 1989 FC.
—CLARK R. CHAPMAN, *Planetary Science Institute*

How do the mechanical, imaging and propulsion systems operate properly on the* Voyager *and* Pioneer *spacecraft considering the extremely frigid conditions existing in the far reaches of the solar system?
—Justin L. MacGregor, Prescott Valley, Arizona

The systems operate properly because the spacecraft keeps its insides warm. Surfaces facing the Sun are painted or covered so that they absorb and reject the right amount of radiant energy. Surfaces facing dark space are insulated to limit their loss of the internal heat generated by operating electrical systems. And, because the *Voyagers* have traveled from near the Sun to far from the Sun, some of their electronic compartments have active thermal control in the form of thermostatic louvers that can close to conserve heat or open to radiate it away.
—JAMES D. BURKE, *Jet Propulsion Laboratory*

FACTINOS

Comet Halley is an oddball of the solar system, according to a group of scientists at Arizona State University in Tempe.

During its 1986 flyby, astronomer Susan Wyckoff and her team measured Halley's carbon-12/carbon-13 ratio using a telescope and spectrometer. They found it to be about 65 to 1, compared to the 89 to 1 ratio measured in all other solar system objects. Halley's high proportion of carbon-13 is closer to that of interstellar dust and gas. [The carbon-13 atom has an extra neutron in its nucleus, making it heavier than the commonest isotope, carbon-12. Both isotopes are believed to have been made inside exploding stars. Their relative quantity gives a clue to the history of the interstellar medium.] The researchers say their analysis suggests that Halley may be an alien body, born fairly recently outside the solar system and captured in a close encounter with the Sun.

Other comet experts are still skeptical about the capture idea. Paul Feldman of Johns Hopkins University in Baltimore says scientists need more comet measurements to determine if Halley truly is an adopted child.
—from F. Flam in *Science News*

Voyager 2 images taken 90 minutes apart on April 3 of this year show a large dark spot and a dark band circling the south polar region of Neptune. The spot, which is 10 percent darker than its surroundings, travels around the planet every 17 to 18 hours. Detection of the spot will help atmospheric scientists to determine rotation rates of Neptune's atmospheric features much sooner than they had expected.

The spot's dimensions, relative to the size of Neptune, are comparable to Jupiter's Great Red Spot.
—from the Jet Propulsion Laboratory's *Voyager Bulletin*

Alan Stern, an astronomer at the University of Colorado, calculates that comets in the Oort Cloud are likely to collide amongst themselves so often that their surfaces will be cratered and fractured to a depth of several hundred feet. This finding conflicts with the general belief that material in the distant Oort Cloud is undisturbed and largely unchanged since the early days of solar system history. Since comets that swing through the inner solar system are unlikely to have a clean, untouched surface, astronomers searching them for primordial solar system material are out of luck unless they can get samples from well below their battered surface layers.

"About once a year some comet hits another," notes Stern. But because the collisions take place at relatively low speeds, "only one comet in a hundred or a thousand has actually been destroyed."
—from *Astronomy*

PLANETFEST '89 PREVIEW!

Special Sales Items and Events!

PLANETFEST '89 Enamel Pin** — Blue and gold Planetfest logo on white enamel background, 1¼" diagonal size. **#671

THE PLANETARY SOCIETY Cloisonne Pin** — FIRST TIME OFFERED — gold lettering on black background, ⅞" diagonal size. **#670

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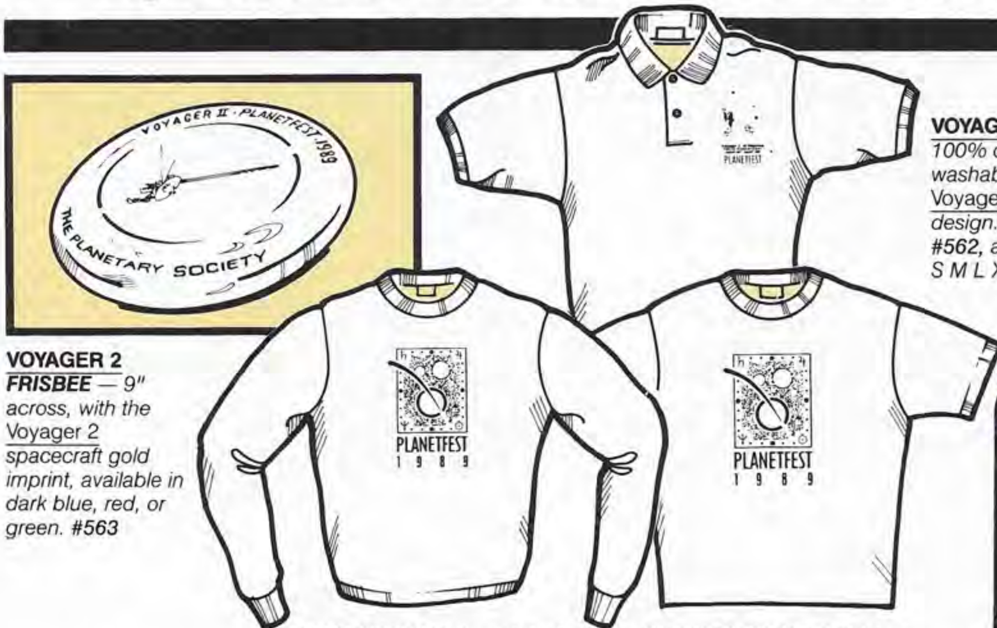

VOYAGER 2 ***Sportshirt** — 100% cotton, machine washable, with the special* Voyager 2 *Neptune encounter design. Available in berry, **#562**, and navy, **#561**, S M L XL sizes.*

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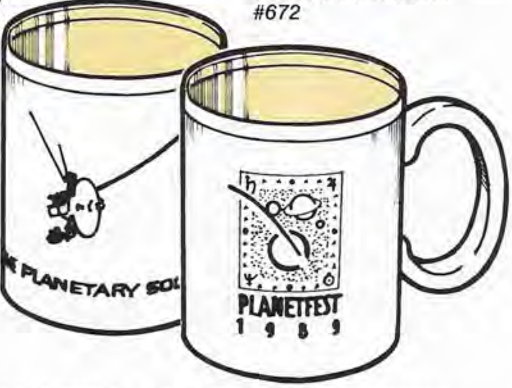
PLANETFEST '89 Sweatshirt** — 50/50 blend, machine washable, with the Planetfest '89 logo design on front. Available in white, S M L XL sizes. **#681

PLANETFEST '89 T-Shirt** — 100% cotton, machine washable, with the Planetfest '89 logo design. Available in white, S M L XL sizes. **#680



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Celebrate *Voyager 2's* Flyby of Neptune!

Come to the Pasadena Center this August for Planetfest '89

Wed., Aug. 23: Symposium #1: A *Voyager* Retrospective. Panelists include Dr. Carl Sagan, Dr. Bruce Murray, and Dr. Edward Stone.

Thurs., Aug. 24: *Voyager* Watch — free to the public — live images of the Neptune encounter all night!

Fri., Aug. 25 - Sun., Aug. 27: Festival events include: Film Festival, Speakers' Forum featuring space program leaders, *Voyager* mission specialists, scientists, educators, writers, etc., exhibits and displays of planetary spacecraft and missions, plus a special, international space art show!

Sat., Aug. 26: "Best of *Voyager*" video presentation, Soviet presentation of Phobos mission results, Science Fiction Writers' Forum.

Sun., Aug. 27: Symposium #2: Beyond Neptune — the future of solar system exploration through international cooperation, featuring space program leaders from the USSR, France, Japan, and the USA. ***And More . . .***

You can pre-register for events over the telephone using a charge card. VISA, MasterCard, and American Express are accepted. Call The Planetary Society's office at

(818) 793-5100.

Hotel accommodations are still available through the Pasadena Visitors Bureau, Telephone: (818) 795-9311.

• New Items

ORDER NUMBER		PRICE (IN US DOLLARS)
561	**Voyager 2 Sportshirt** – 100% cotton, navy blue S M L XL	$28.00
562	**Voyager 2 Sportshirt** – 100% cotton, berry S M L XL	$28.00
563	**Voyager 2 Frisbee** – 9″ dark blue, red, green (specify color)	$ 3.50
264	**Fannypack** – silver & black	$13.00
265	**Coffee Mug** – The Planetary Society, dark blue, light blue, white (specify color)	each $ 8.00 (set of four) $28.00
670	**The Planetary Society Cloisonné Pin** – gold lettering on black background	$ 4.00
671	**Planetfest '89 Enamel Pin** – Planetfest logo on white background	$ 4.00
672	**Set of Two Pins** – Planetfest '89 and The Planetary Society	$ 7.00
673	**Glitter Pencils in a Tube** – Planetfest '89 logo	$ 5.00
674	**Glitter Pencils in a Tube** – The Planetary Society logo	$ 5.00
675	**Glitter Pencils** – different colors	each $ .25
676	**Key Ring** – The Planetary Society logo	$ 5.00
677	**Key Ring** – Planetfest '89 logo	$ 5.00
680	**Planetfest '89 T-Shirt** – 100% cotton, white S M L XL	$14.00
681	**Planetfest '89 Sweatshirt** – 50/50 blend, white S M L XL	$20.00
682	**Planetfest '89 Coffee Mug** – blue	each $ 8.00 (set of four) $28.00
685	**Planetfest '89 Decals** – (5 for $4.00)	each $ 1.00

Many Planetfest items will not be available until Aug. 23, 1989

• Books

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129	**Living in Space–A Manual for Space Travellers** by Peter Smolders. 160 pages.	$13.50
133	**Mirror Matter: Pioneering Antimatter Physics** by Robert L. Forward and Joel Davis. 262 pages.	$17.00
140	**Out of the Cradle: Exploring the Frontiers Beyond Earth** by William K. Hartmann, Ron Miller and Pamela Lee. 190 pages.	$11.00
148	**Planets Beyond: Discovering the Outer Solar System** by Mark Littmann. 286 pages.	$20.50

• Books (cont.)

ORDER NUMBER		PRICE (IN US DOLLARS)
152	**The Quickening Universe: Cosmic Evolution and Human Destiny** by Eugene T. Mallove. 268 pages.	$17.00
157	**Starsailing: Solar Sails and Interstellar Travel** by Louis D. Friedman. 146 pages.	$ 9.00
158	**Space–The Next 25 Years** by Thomas R. McDonough. 237 pages.	$16.00
165	**The Grand Tour: A Traveler's Guide to the Solar System** by Ron Miller and William K. Hartmann. 192 pages.	$10.00
170	**The Home Planet** edited by Kevin W. Kelley. 256 pages.	$36.00
184	**The Search for Extraterrestrial Intelligence: Listening for Life in the Cosmos** by Thomas R. McDonough. 256 pages. **Soft Cover**	$13.50
185	**The Surface of Mars** by Michael Carr. 232 pages.	$20.00

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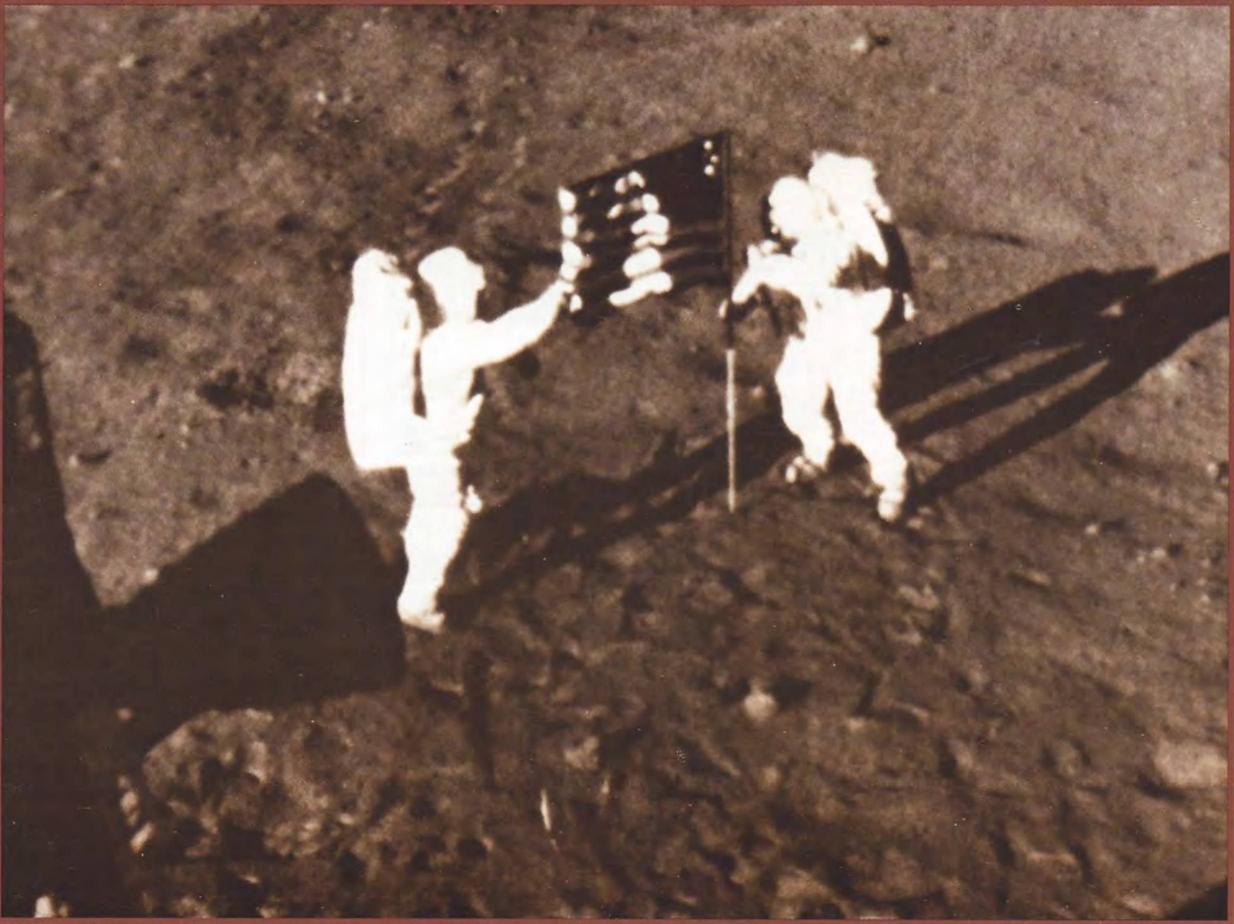

It's now been 20 years since human beings first left their footprints in the lunar soil. Here, Neil Armstrong and Buzz Aldrin erect the flag in the only photo that Apollo 11 returned of the astronauts together on the Moon. Twenty years later, thoughts of the Apollo era evoke the nostalgia we reserve for a cherished memory. But past is prelude, and we focus our yearnings on the future. **Photo: Johnson Spaceflight Center**

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