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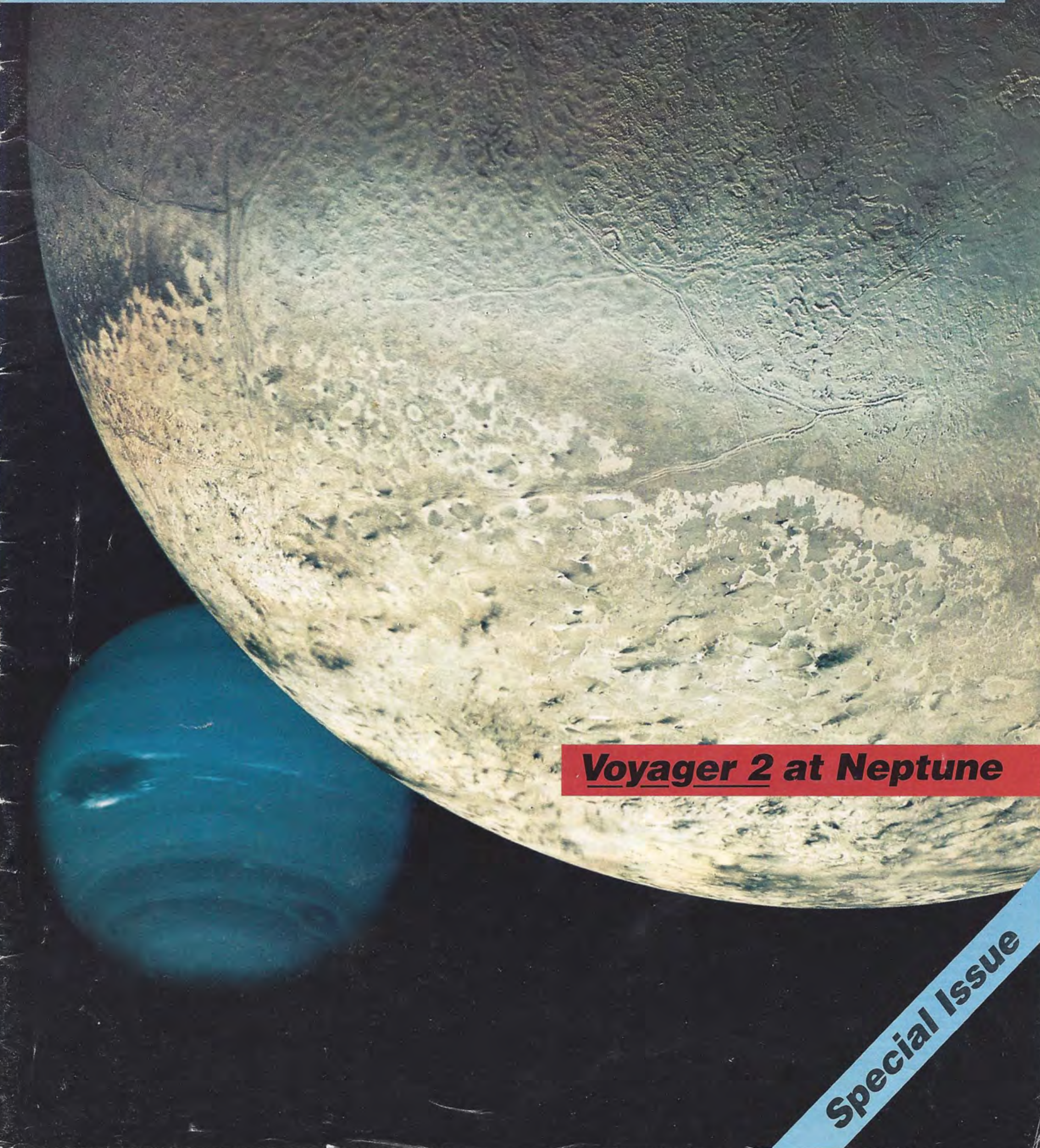

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COVER: From the edge of our planetary system, the spacecraft* Voyager 2 *transmitted back to Earth images of Neptune, its large moon Triton, its strange ring system and its retinue of small satellites. In this montage constructed from high-resolution images, the south pole of Triton dominates, with cloud-streaked Neptune in the background. The flyby of Neptune in 1989 was the last* Voyager *planetary encounter. These two doughty spacecraft opened up the outer solar system for scientific exploration, and we shall not see their like again.

Montage: Alfred McEwen, US Geological Survey, Flagstaff

FROM THE EDITOR

It had been like reading a wonderful adventure book, one you never want to end. At the close of the last chapter, you feel a gentle melancholy because you can never relive your first experience of meeting these characters and sharing their story.

That was how I felt in 1989 at the end of *Voyager*'s last encounter. As a member of the press, I had participated in the mission only vicariously. Still, for 12 years I felt as if I had flown with *Voyager,* first to Jupiter and Saturn, then on to Uranus and Neptune.

Through *Voyager*'s robotic eyes, I had peered into the heart of Jupiter's Great Red Spot, I had watched the "spokes" dance around Saturn's elegant rings and I had marveled at the bizarre terrain of Uranus' moon Miranda. Finally, I had gazed back at Neptune and its moon Triton knowing this was the last time *Voyager* and I would visit a planet together.

I had shared these moments not only with members of the *Voyager* project team, but with people around the world. The two *Voyager* spacecraft—with a muted transmitter, an arthritic scan platform and assorted other ills—had captured the hearts of the public as perhaps no other spacefaring robots ever had. They were explorers, and they were survivors.

Launched in 1977, *Voyagers 1* and *2* had followed the aptly named *Pioneer 10* to Jupiter. In March 1979, *Voyager 1* reached this monarch among planets and made the first of the epic string of discoveries that came to distinguish the mission. The spacecraft showed us that, like Saturn, Jupiter was circled by a ring. Perhaps most memorably, *Voyager 1* caught a volcano in the act of erupting on the moon Io.

Then the spacecraft followed the path blazed by *Pioneer 11* to Saturn, *Voyager 1* arriving in November 1980 and *Voyager 2* in August 1981. There they discovered that the famous rings are actually made of thousands of thin, tenuous ringlets. The images they returned to Earth also revealed the "spokes" of charged particles and the "kinks" that complicated our understanding of planetary rings. The *Voyager*s also investigated the dense nitrogen atmosphere of Saturn's largest moon, Titan, and discovered that it is a veritable factory for organic compounds.

After Saturn, the *Voyagers'* paths diverged: *Voyager 1* swung northward, heading out of the ecliptic plane in which the planets orbit; *Voyager 2* entered undiscovered territory and became the first emissary from Earth to visit Uranus and Neptune.

As *Voyager 2* flew by those distant worlds, everything it saw or sensed was a first. In 1986 it reached Uranus, the first planet discovered since antiquity. With a bland face and a bizarre magnetic field, coal-black rings and battered little moons, Uranus surprised, baffled and intrigued the team. And it whetted their appetites for the last encounter, with the Neptune system in August 1989.

As the spacecraft approached its final target, anticipation of both new findings and the mission's completion jumbled the feelings of team members and project watchers alike. Earth-based observations seemed to suggest that the neptunian system might encompass phenomena even stranger than those seen at Jupiter, Saturn and Uranus.

Was Neptune circled by discontinuous arcs where complete rings should be? Were there lakes of liquid nitrogen lying on Triton's surface? Would Neptune's magnetosphere conform to the norm, or would it behave as strangely as that of

(continued on page 24)

Members' Dialogue

As administrators of a membership organization, The Planetary Society's Directors and staff care about and are influenced by our members' opinions, suggestions and ideas about the future of the space program and of our Society. We encourage members to write us and create a dialogue on topics such as a space station, a lunar outpost, the exploration of Mars and the search for extraterrestrial life.

Send your letters to: Members' Dialogue, The Planetary Society, 65 N. Catalina Avenue, Pasadena, CA 91106.

Louis D. Friedman's statements regarding space station *Freedom* (SSF) and science in World Watch and "An Executive Report to Members" in the November/December 1991 issue of *The Planetary Report* are not true and are divisive within the space community. The statements I refer to are, "In an extraordinary display of unity, many government advisory groups and national scientific organizations have stressed that *Freedom* will do very little either for science or for exploration . . ." and "The Officers of The Planetary Society argued against building space station *Freedom* as it is now designed, yet Congress funded it—to the detriment of space science and exploration."

It is not true that there was an extraordinary display of unity among government advisory groups and national scientific organizations. On the contrary, the Aerospace Medical Advisory Committee, the Space Science and Applications Advisory Committee (SSAAC), the Life Sciences Advisory Subcommittee of SSAAC, the Committee on Space Biology and Medicine (Space Studies Board of the National Research Council), the Augustine report, the Stafford report, the American Physiological Society, the Aerospace Medical Association, the American Society for Space and Gravitational Biology, the American Academy of Otolaryngology–Head and Neck Surgery, and the American Institute of Biological Sciences were all on record that SSF is essential for science and exploration. The science users of SSF will be materials scientists and life scientists, and human exploration cannot proceed without a space station to solve certain life science problems encountered during long-duration spaceflight, including physiological, psychological and life support problems.

These statements reflect the author's narrow view of science. Life science is also a science and, like materials science, will benefit greatly from SSF. To leave the life sciences out of science is unwise, if only because it invites the wrath of a science community that in terms of numbers is larger than all of the other space science communities combined. *Freedom* will allow the generation of data that are useful both to the space effort (they will enable human exploration) and to medical problems (such as osteoporosis) and other problems on Earth.

Space scientists should work together rather than oppose one another. Both the life sciences and the physical sciences are important. We need one another. The upcoming repair of the Hubble Space Telescope is an obvious example.
—FRANCIS J. HADDY, *Bethesda, Maryland*

We are in complete agreement with Dr. Haddy that life science research in Earth orbit is important and should be supported. Such research is central to any human exploration of the solar system. However, space station Freedom *won't be able to support this research for many years, and we (and most life scientists) believe that there are much better ways to advance life sciences and human planetary flight than the present SSF plan.*

Several of the groups Dr. Haddy cites are NASA-funded organizations, whereas I was referring to the more independent professional science organizations, which banded together to issue a statement just prior to the final Senate vote. I would also argue that the Augustine and Stafford reports damned space station Freedom *by faint praise.*

The cancellation of the Comet Rendezvous Asteroid Flyby and curtailment of Magellan *(see page 26) are this year's space science casualties of last year's battle over the space station. —Louis D. Friedman, Executive Director*

The Planetary Report's November/December 1991 articles regarding asteroids, comets and meteorites presented the facts that the people of Earth truly have a potentially serious issue to debate and that some action will eventually be required. It's sad to think that perhaps in order to initiate such global action, it may require the presence of an asteroid with Earth as its imminent target.
—BILL MERKES, *Freeland, Washington*

NEWS BRIEFS

NASA scientists now say that an ozone hole may be widening over populated regions of North America, Europe and Asia. NASA's Upper Atmospheric Research Satellite has reported high levels of chlorine monoxide in the upper atmosphere over London, Moscow and Amsterdam. Chlorine monoxide is a free radical that separates itself from chlorofluorocarbons and destroys the ozone layer.

"We are no longer dealing with remote, high-latitude areas," says NASA's Michael Kurylo. "The data show we are dealing with a problem that extends to populated regions of the Northern Hemisphere."
—from Steve Scauzillo in the Pasadena *Star-News*

Magellan successfully began its third radar mapping cycle on January 24, despite earlier transmitter problems. The spacecraft's primary transmitter stopped functioning on January 4, and engineers had to turn to the ailing backup transmitter.

A new operational mode was devised for the backup transmitter. This will allow it to continue mapping the planet, but at less than half the previous rate.
—from the Jet Propulsion Laboratory

Last year Congress slashed funds for many of NASA's planned science projects, offering instead $137 million for new programs that the space agency hadn't realized it needed. One new project was an "advanced liquid dispensing technology evaluation" promoted by lobbyists for the soft drink industry. By the time Congress was through, NASA and space shuttle astronauts were amazed to learn that austerity had doomed the space infrared telescope, the orbiting solar laboratory, the flight telerobotic server and seven other research projects—but not a plan to design a dispensing machine that would allow orbiting astronauts to choose between Coke and Pepsi.
—from *The Bulletin of the Atomic Scientists*

The Elusive Rings of *Neptune*

by Carolyn C. Porco

The year 1989 was a banner one for scientists enthralled with planetary rings, those decorative appendages encircling all the gaseous planets in the outer solar system. In late August, nearing the end of its epic 12-year journey across the solar system, *Voyager 2* paid a visit to the distant blue planet Neptune.

Very little was known about Neptune or its rings before *Voyager* arrived there—so little, in fact, that some scientists vociferously doubted the existence of neptunian rings right up to the bitter end. Not that anyone could blame them. Neptune's rings had been elusive, and the story of their pursuit illustrates both the joys and the pitfalls of scientific investigation.

The Pursuit Begins

With the discovery of the uranian rings in 1977 and the stunning but unsettling realization that Saturn was not the only ringed planet, planetary astronomers began to search for rings around the other outer planets. *Voyager 1* uncovered Jupiter's ring in 1979, leaving Neptune the sole remaining ringless giant planet.

The first big chance for astronomers to check out Neptune came in 1981. In its orbit around the Sun, Neptune passed nearly in front of three stars that year. In one instance, observed from the Catalina Mountains near Tucson, Arizona, the star's light was dimmed by an opaque object some 180 kilometers (110 miles) in diameter, presumably in orbit around Neptune. The event was not mirrored, however, on the other side of the planet, so the occulting object was obviously not a continuous ring. Instead, the occultation was attributed to a previously unknown neptunian satellite, tentatively called 1981N1.

Nothing else in the vicinity of Neptune was observed that year or the next. Nevertheless, efforts continued. Another stellar occultation by Neptune was observed in the summer of 1983 at observatories in Australia, Tasmania and Hawaii—with negative results. Finally, circum-neptunian material only 15 to 20 kilometers (9 to 12 miles) wide occulted three stars in the summers of 1984 and 1985—each time, on only one side of the planet.

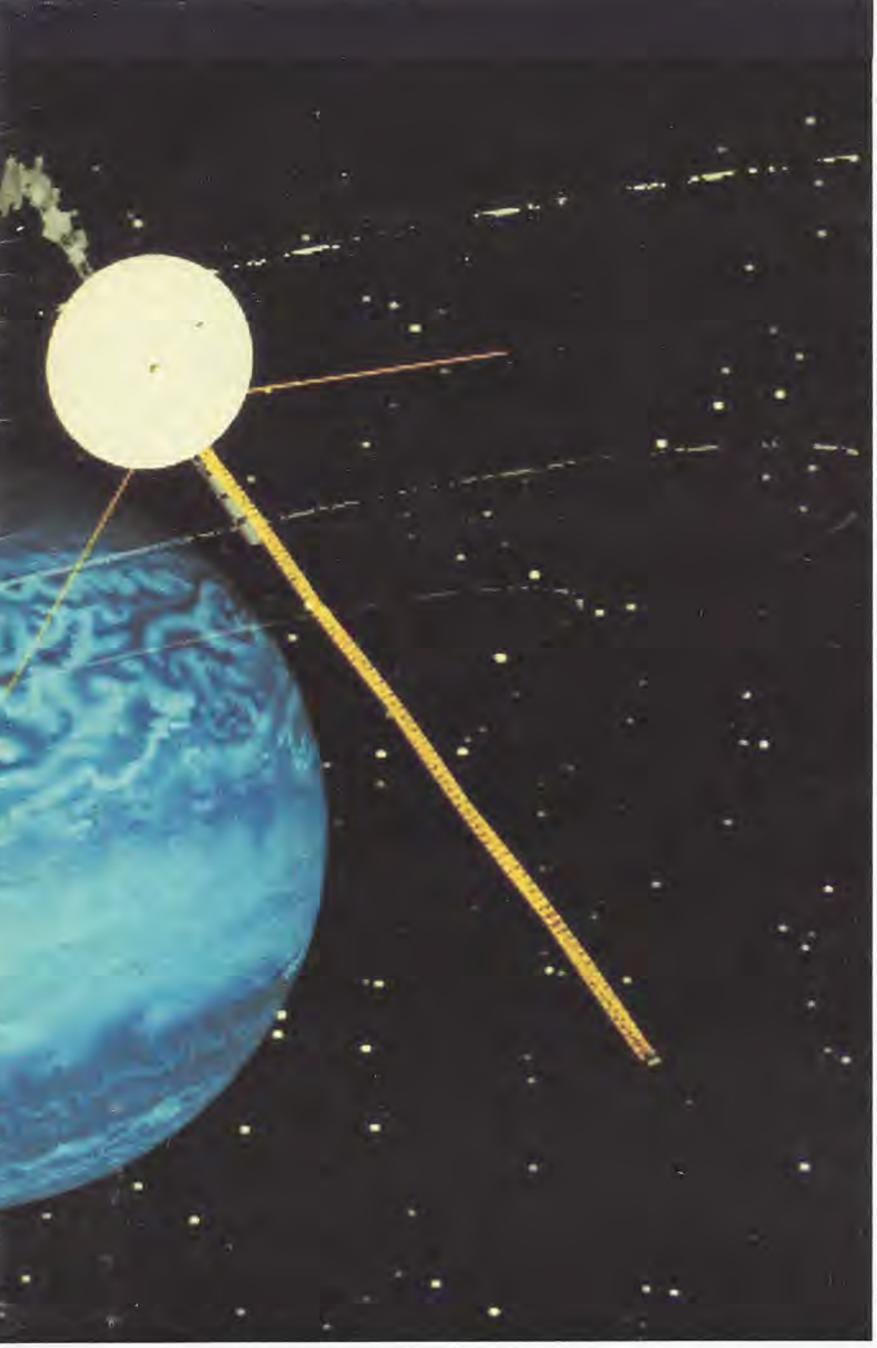


Figure 1 — This is the view of Neptune and its rings as we thought they would look — before Voyager 2 *encountered the planet. Perplexing observations from Earth had led scientists to postulate that Neptune was orbited by dozens of ring arcs, rather than complete rings like those encircling Jupiter, Saturn and Uranus. The spacecraft proved this view wrong: Neptune possesses complete but tenuous rings, with only one punctuated with dense sections that appeared to observers on Earth and to* Voyager 2 *as the ring arcs.*

Computer graphic: JPL/NASA

The Birth of the Ring Arc Theory

So was born the idea that Neptune did not have rings as we had come to know them, but instead had very narrow, tenuous and incomplete rings, called ring arcs. These features were nothing at all like the massive rings of Saturn or the narrow but substantial and complete rings of Uranus. This idea became so pervasive that the original 1981 satellite detection was, in some circles, discounted as being improbable and was attributed to an optically thick, wider-than-average ring arc.

By August 1989, more than 50 stellar occultations by Neptune had been observed. Yet only a handful produced believable sightings of ring material, and only three of these were confirmed at more than one telescope.

From this collection of successes and failures emerged the widely accepted view that the vicinity of Neptune was populated by perhaps dozens of ring arcs, ranging from 100 to 1,000 kilometers (about 60 to 600 miles) in length, distributed in the equatorial plane of the planet as shown in Figure 1. By analogy with the uranian rings, the material comprising the Neptune ring arcs was thought to be exceedingly dark, with a reflectivity no brighter than that of charcoal. And most, if not all, of the arcs would be very narrow.

Where Can a Ring Arc Come From?

The possibility of a new variety of ring feature intrigued theorists, who wondered how narrow arcs could be prevented from spreading. After all, it would take only about three years for a clump of ring material 15 kilometers (about 9 miles) wide to form a 360-degree ring. This happens because material on the inside of the clump orbits faster than, and eventually catches up with, material on the outside, completing a circuit around the planet. Maybe the arcs weren't very old. But in the belief that they were, several mechanisms to confine them were proposed.

One of these mechanisms suggested that arcs could be confined in both length and width by the combined action of perturbations arising from a set of gravitational resonances produced by a single, nearby satellite. One kind of satellite resonance would keep material confined in length, while the other would help keep it confined in width. This theory required that the satellite be about 200 kilometers (120 miles) in diameter and that its orbit be inclined to that of the arcs. *Voyager* would surely be capable of detecting such satellites if they were there.

Voyager at Work

Planning for *Voyager*'s encounter with Neptune began shortly after the spacecraft left the Uranus system in 1986. Narrow ring widths, inherently dark material and the low sunlight levels at Neptune all called for very long camera exposure times, longer than those *Voyager* investigators had used in the Uranus encounter. New algorithms were programmed into the spacecraft's computer to stabilize the scan platform carrying the cameras. The camera-commanding software was rewritten to allow for extremely long exposures, in some cases as long as 30 minutes. With *Voyager 2* readied for its encounter with Neptune, the countdown began.

Sixty-four days before its closest approach to Neptune, *Voyager* found Proteus, 400 kilometers (about 250 miles) in diameter. Larger than the previously known satellite Nereid, Proteus orbits Neptune at a distance of 118,000 kilometers (about 70,000 miles). But no ring arcs were seen.

By four weeks before closest approach, three more moons—Larissa, Despina and Galatea—had all been uncovered. (Larissa turned out to be 1981N1, discovered from Earth.) Still, no ring arcs were found.

Then, on August 11, 1989, when *Voyager* was only two weeks and 20 million kilometers (about 12 million miles) away, and closing in at a swift 17 kilometers (11 miles) per second, it detected the very arcs that had been so difficult to snare from Earth. They looked, of course, nothing like what we had imagined—not small bits of ring scattered here and there, but several arcs, like beads strung out on a faint and narrow string.

The following two and a half weeks saw the unveiling of the entire neptunian ring and inner satellite system. During that time, the *Voyager* cameras acquired about 800 images of the rings and discovered two more satellites, Thalassa and Naiad. The *Voyager* photopolarimeter and ultraviolet spectrometer experiments both successfully observed a stellar occultation by one of the arcs, confirming results obtained in similar ground-based experiments.

Figure 2 — Backlighted by the Sun (and with the bright planet blocked out), the thin neptunian rings become visible. The three most prominent rings are named for the men who shared the discovery of Neptune in 1846: John Couch Adams and Urbain Jean Joseph Leverrier independently calculated the planet's position and Johann Galle found it. A more diaphanous ring, N4R, appears between Leverrier and Adams, and another discovery of* Voyager 2, *N5R, is not quite visible here between N4R and Adams.

Image: JPL/NASA

Sifting Through the Data

The two and a half years that have passed since *Voyager*'s encounter with Neptune have brought new insights and discoveries, gleaned from the analysis and interpretation of these precious bits of information. What have we learned?

Neptune is surrounded by several continuous and very dusty rings, which show up best when backlighted by the Sun (Figure 2). The arcs are actually part of the diffuse and narrow Adams ring, 10 times less substantial than the arcs themselves, orbiting at a distance of 62,932 kilometers (about 39,000 miles) from Neptune. Another ring, Leverrier, sits 53,200 kilometers (about 33,000 miles) from Neptune and appears equally narrow and diaphanous. Each narrow ring is attended by a satellite—Adams by Galatea and Leverrier by Despina—orbiting within 1,000 kilometers (about 600 miles) of it.

Galatea, 160 kilometers (about 100 miles) in diameter, is itself co-orbiting with what appears to be very tenuous and perhaps discontinuous ring material, which is so faint it is barely visible in *Voyager* images. Extending out from Leverrier is a plateau of material, about 4,000 kilometers (2,500 miles) wide, bounded by a narrow feature that may be a separate ring. (Both of these features have yet to receive official names. They are provisionally called 1989N4R and 1989N5R.) Finally, there is the Galle ring, 1,700 kilometers (about 1,100 miles) wide. At 42,000 kilometers (26,000 miles) or-

Resonances in the Rings

When one child pushes another in a playground swing, steadily increasing the height of the ride, we observe resonance. The pushes are timed so as to add energy. The word *resonance* itself refers to sound (singing in the shower or the squeal of loudspeakers in a maladjusted public-address system), but the concept is applied to any periodic phenomenon that can be driven by correctly timed pulses. In the accompanying article the pulses are provided by the mutual gravity of ring particles and small satellites orbiting near each other. The resonances caused by the satellites could perturb the ring particles' orbits and confine these tiny bodies in the clumps seen from Earth as ring arcs. *—James D. Burke* bital radius, it is the innermost of Neptune's rings. The Galle ring, Galatea's companion ring, 1989N4R and 1989N5R are about 100 times less optically thick than Adams or Leverrier.

Light from the planet falling onto the camera aperture, scattering within the optics and ultimately falling onto the detector is normally too faint to see unless the planet is in the camera's

field of view. But this light can be overwhelming in the minutes-long exposures required to see Neptune's rings. For this reason, it is difficult to say with certainty whether any extended ring material exists very close to Neptune. Consequently, the possibility of a continuous, diffuse sheet of dust extending from inside Leverrier all the way down to the planet cannot be discounted.

Jewels in the Crown

The arcs are undeniably the precious jewels in the delicate rings that crown the globe of Neptune, and most of the attention devoted to the rings during *Voyager*'s encounter was lavished on them. *Voyager*'s highest-resolution ring images were all targeted to the arcs after previous images had been used to determine their orbits. One arc was even captured as *Voyager* plunged through the ring plane (Figure 3). Although only three features have been officially named—Liberté, Égalité and Fraternité—there are actually five distinct arcs, all contained within a 40-degree region (Figure 4). Four of the arcs are less than 4,400 kilometers (about 2,700 miles) long; the fifth and trailing one is 10,500 kilometers (about 6,500 miles) long.

All of Neptune's dusty rings brighten up when backlighted by the Sun, in the same way that the dust on a car windshield becomes very much more apparent when one drives toward the Sun. But the arcs brighten up most of all, indicating a dust content larger than in the other rings.

Estimates of the production rate of dust by micrometeoroids striking the rings of Neptune are a hundred, perhaps a thousand, times too small to explain the abundance of arc dust observed. The only viable alternative is that dust is created when larger-than-average particles in the arcs, moving at relative velocities of several meters per second, collide with one another. These velocities would be about a thousand times greater than the collisional velocities between the particles in Saturn's rings.

Closing In on an Explanation

Certainly the most intriguing aspect of the arcs is the mechanism by which they are maintained, and many lines of evidence suggest that Galatea may be single-handedly responsible for the arcs' appearance. The satellite is large enough and close enough to the arcs

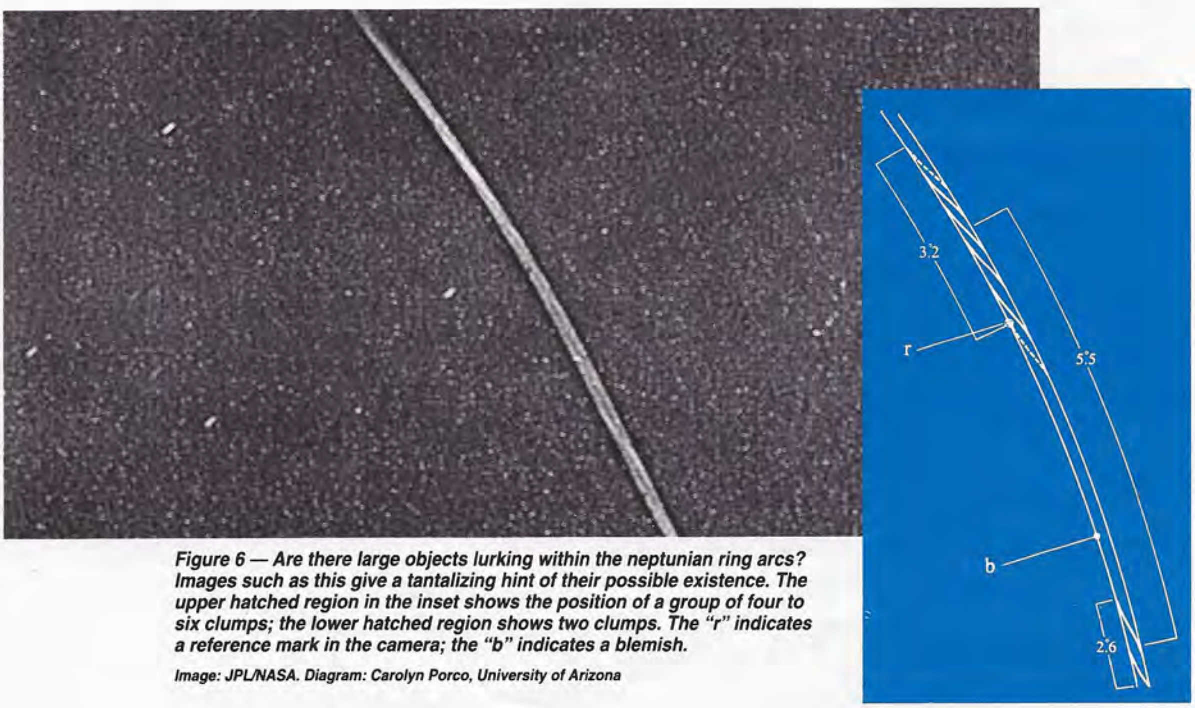
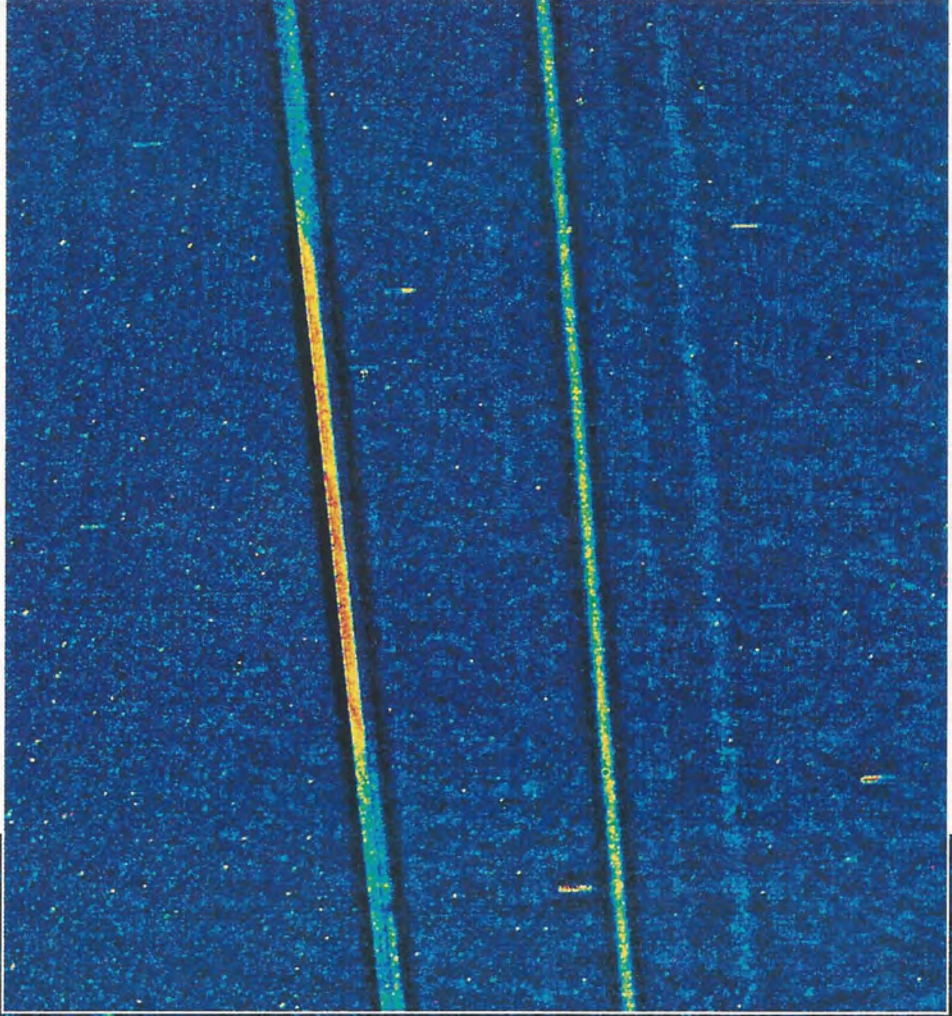


Figure 6 — Are there large objects lurking within the neptunian ring arcs? Images such as this give a tantalizing hint of their possible existence. The upper hatched region in the inset shows the position of a group of four to six clumps; the lower hatched region shows two clumps. The "r" indicates a reference mark in the camera; the "b" indicates a blemish.

Image: JPL/NASA. Diagram: Carolyn Porco, University of Arizona



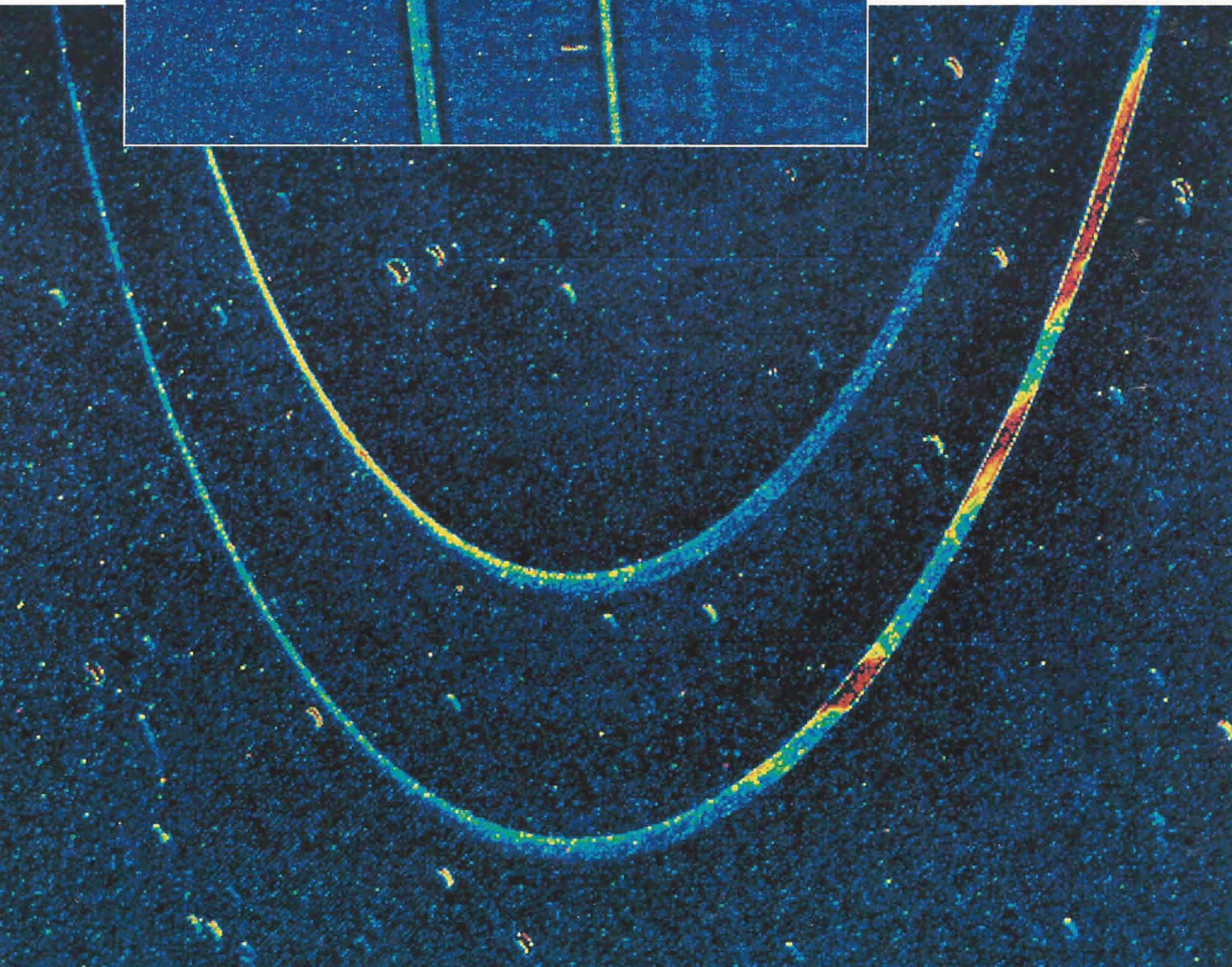


Figure 3 (left) —
As Voyager plunged through the ring plane, its wide-angle camera captured the entire ring system in a compressed view. One of the arcs in the Adams ring is clearly visible.

Figure 4 (below) —
With image processing, the three named arcs in Neptune's rings were revealed to be five arcs, seen here on the right as the red and yellow segments in Adams, the outside ring. The first four arcs are less than 4,400 kilometers long; the fifth and trailing arc is 10,500 kilometers long.

Images: Carolyn Porco, University of Arizona

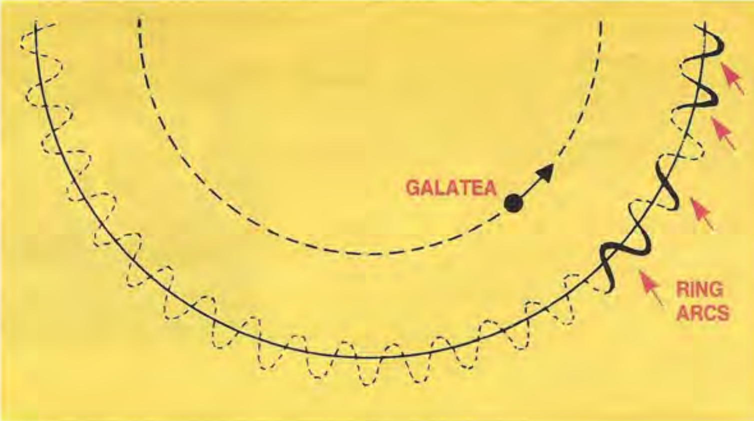


Figure 5 — The interactions between the small moon Galatea and the ring particles not only maintain the arcs' positions but produce an interesting scalloped wave pattern in Neptune's rings. If you were to track the arcs as they orbited the planet, it would appear as if a wave were traveling through the arcs at Galatea's orbital speed.
Illustration: Ron Miller

to provide the two types of gravitational resonances required for single-satellite arc confinement. Its orbit is inclined to the arcs' orbit by a small but adequate 0.02 degree.

Moreover, all the arcs, with one exception, are less than 4,400 kilometers long, the longitudinal distance over which Galatea's confining action would be expected to operate. Finally, the ring particles within the arcs are on distinctly noncircular orbits, arranged around Neptune in such a way that every 8.57 degrees or 9,415 kilometers (5,850 miles) along the arcs they find each other at the same orbital phase. That is, if one were to study the arcs as they orbit Neptune, it would appear as if a scalloped wave pattern with a 9,415-kilometer wavelength were traveling through the arcs at Galatea's orbital speed (Figure 5), causing the arcs to bow in and out by 30 kilometers (about 19 miles)—a convincing manifestation of Galatea's gravitational perturbations.

Interparticle collisions occurring at several meters per second within the arcs are a natural consequence of Galatea's perturbations, and they provide a cogent explanation for the large arc dust content. But collisions are also the bane of the arcs' existence, as they can eventually disrupt arc confinement. Maybe big bodies, several kilometers in size, within the arcs can help reduce the destabilizing effects of collisions while providing the source for arc dust.

Do big bodies exist within the arcs? Perhaps. Several *Voyager* images revealed brighter-than-average knots or clumps within the arcs, separated by about 550 to 1,100 kilometers, or 340 to 680 miles (Figure 6, page 7). Though it is unclear if these features are the manifestations of big bodies, it is a provocative thought.

Something Different

In all, *Voyager 2* discovered six new satellites around Neptune. Four of them—Galatea, Despina, Thalassa and Naiad—fall well within the ring region and are substantial bodies, ranging from 50 to 180 kilometers (about 30 to 110 miles) in diameter. This arrangement is dramatically different from those observed in the other outer planetary systems. There, only the very smallest satellites, about 20 kilometers (12 miles) in diameter, orbit at the outer limits of each planet's rings. If we compare the total mass within Saturn's rings with that contained within the confines of Neptune's rings, we would find that Saturn wins, but only by about a factor of 5. Yet almost all the saturnian mass is contained in rings, whereas almost all the neptunian mass is contained in satellites.

Current wisdom says that rings were not born alongside their parent planets, but instead are the result of the catastrophic breakup of a planetary satellite. They are also believed to be temporary fixtures, lasting perhaps no longer than 100 million years. If this is true, then it is possible that long ago, when dinosaurs still roamed Earth, the rings of Saturn resided in an icy body not unlike the saturnian satellite Mimas (Figure 7). Even more compelling a thought is this: A time may come in the distant future when the inner satellites of Neptune, pulverized by cometary collisions or torn asunder by neptunian tides, spread their remnants far and wide and form a glorious array of rings to rival those of Saturn.

Figure 7 — The saturnian satellite Mimas exhibits a very large crater, Herschel, created in an impact that came very close to smashing this moon to bits. Other, less fortunate satellites might have suffered the ultimate blow and been transformed into the rings of Saturn. Someday the same fate may befall a neptunian satellite, creating rings to rival those of Saturn.
Image: JPL/NASA

Carolyn Porco is an associate professor in the Department of Planetary Sciences/Lunar and Planetary Laboratory of the University of Arizona in Tucson. She was a member of the Voyager *imaging team, and is now the leader of the imaging team for the* Cassini *mission back to Saturn and its rings.*

The Magnetosphere of Neptune

by S.M. Krimigis

Before *Voyager 2*'s encounter with Neptune in 1989, most scientists expected that Neptune would have a magnetic field and an associated magnetosphere. All the giant planets visited so far had displayed fascinating electromagnetic features—for example, Jupiter's magnetosphere is the largest object within our solar system, and Uranus' magnetosphere is one of the strangest yet encountered (see the November/December 1986 *Planetary Report*). *Voyager*'s discovery of a magnetosphere was therefore no surprise. However, its nature has raised many questions. To understand *Voyager*'s findings, we first need to look at more familiar territory—the magnetic field and magnetosphere of Earth.

Earth's magnetic field is roughly aligned with the planet's axis of rotation, and it rotates with Earth once every 24 hours. The atmosphere as we know it extends only to a few tens of kilometers altitude. By about 100 kilometers (60 miles), much of it has become ionized by solar radiation—that is, the neutral atmospheric atoms have become positively or negatively charged by losing or gaining one or more electrons.

Before the late 1950s and the onset of the space age, the region beyond about 100 kilometers was thought to be relatively empty of matter. *Explorer 1*, the first American satellite, discovered that this space is actually full of electrons and ions that have been boosted to tremendously high energies.

These particles are generally concentrated into two intense radiation belts, the Van Allen belts (named after their discoverer, James A. Van Allen, an advisor to The Planetary Society). Trapped in stable orbits within Earth's magnetic field, the particles have such high energies that they are able to penetrate an inch of steel, thus posing radiation hazards to the health of astronauts who might be orbiting for extended periods. Astronauts on the space shuttle

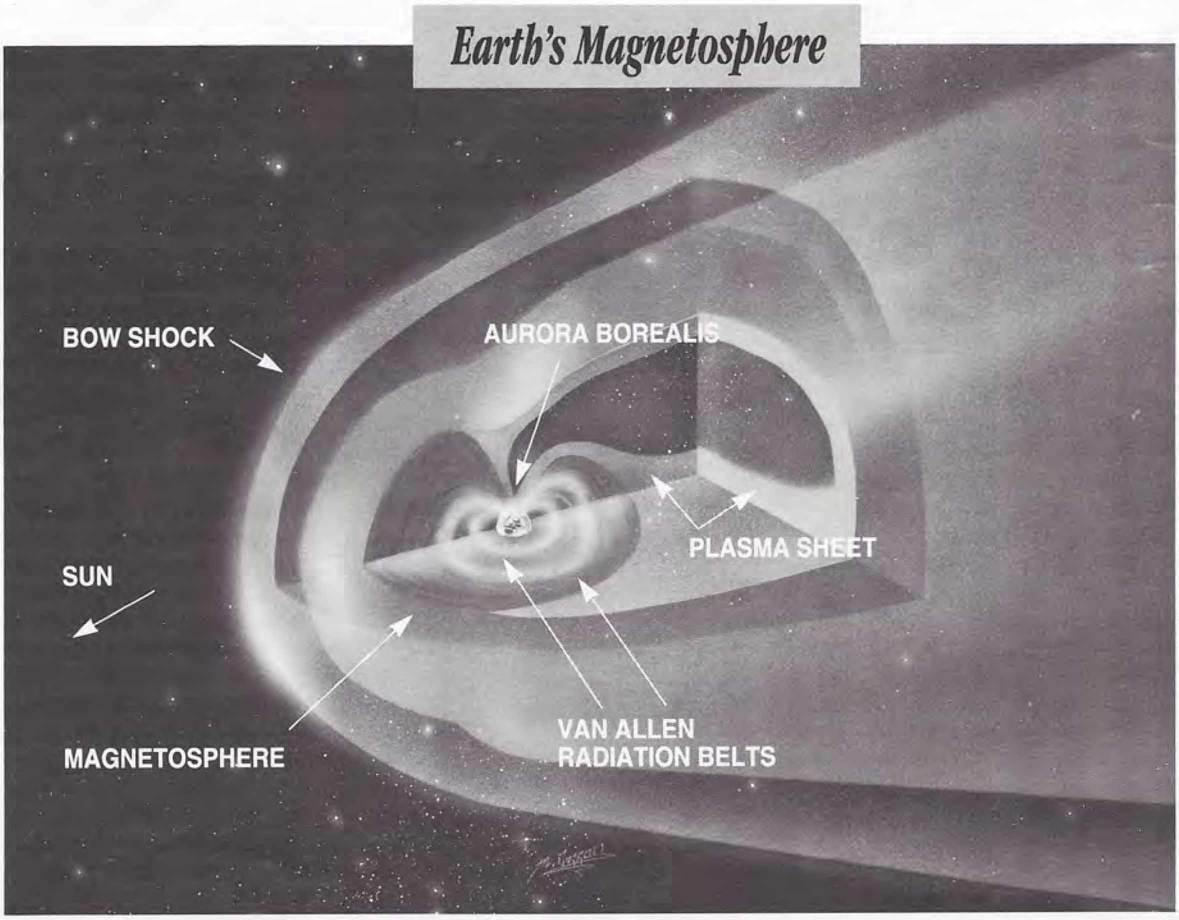


Figure 1 — Earth's magnetosphere is formed by the interaction of the solar wind with the planet's intrinsic magnetic field. The solar wind compresses the magnetosphere on the dayside while stretching it out on the opposite side of the planet. Various plasma populations, as well as concentrations of charged particles such as the Van Allen radiation belts, are produced by processes not yet fully understood by scientists.

Illustration: Michael Carroll

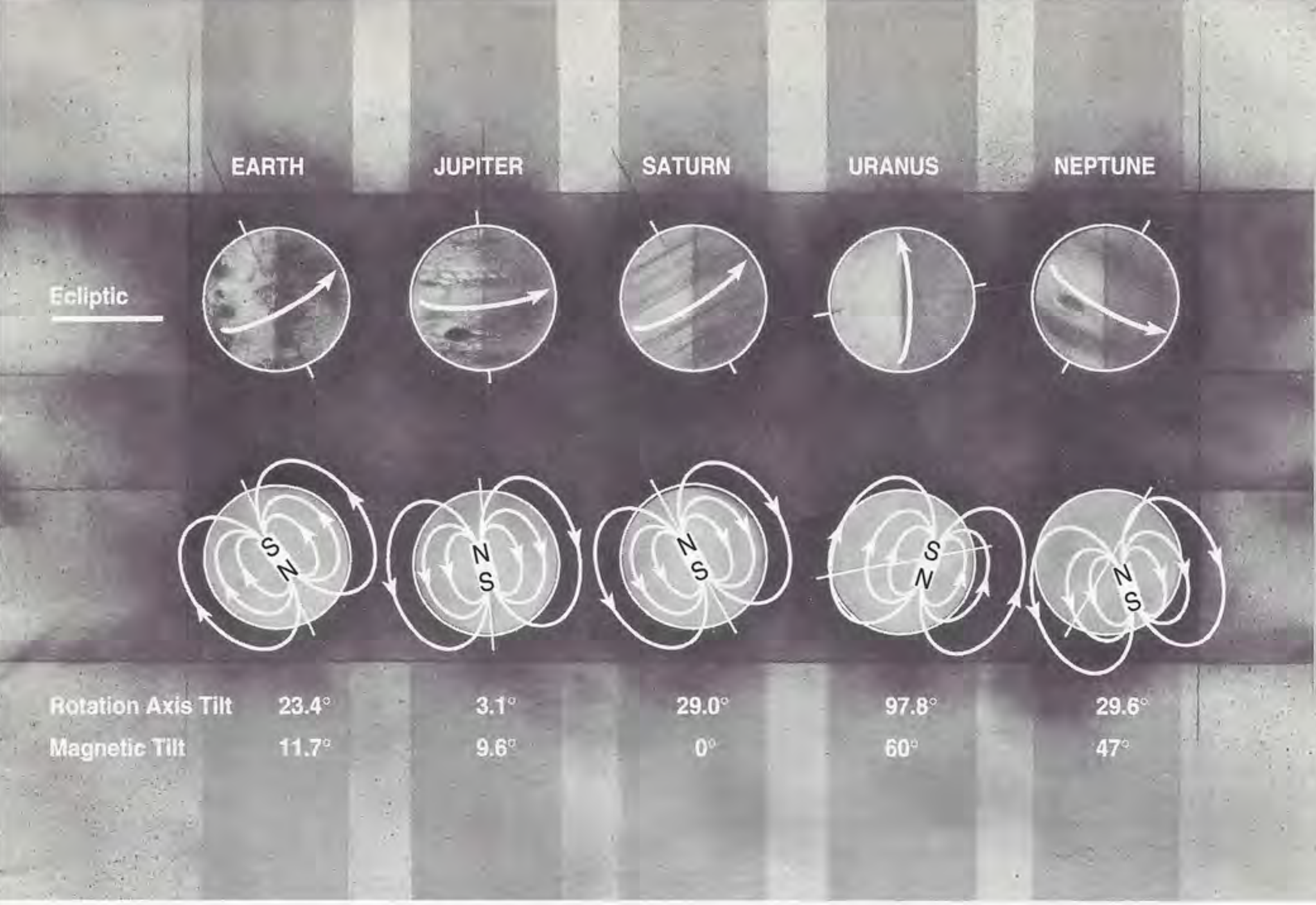


Figure 2 — Here we compare the relationships between the magnetic axes and rotation axes of the planets having substantial magnetospheres. The angle between the two axes is greatest for Uranus. Scientists once thought that this tilt was due to the orientation of Uranus' rotation axis, which makes the planet appear to be spinning on its side. The large tilt of Neptune's magnetic axis, however, suggests there is probably another explanation.

Illustration: S.A. Smith

and cosmonauts on *Mir* orbit Earth within the region of safe flight below 400 kilometers (150 miles). The men who flew to the Moon passed through this region quickly, so their exposure to the radiation was limited.

In addition to the Van Allen belts, Earth's magnetosphere (so called because it is dominated by Earth's magnetic field) is filled with electrons and ions of lower energies. These extend to an altitude of 80,000 kilometers (about 50,000 miles) on the side of Earth facing the Sun (the dayside) and at least 6 million kilometers (about 3.7 million miles) on the side of Earth away from the Sun (the nightside).

As Figure 1 shows, the envelope of this magnetosphere is asymmetric, because of the solar wind, a flow of plasma that is continuously emitted by the Sun at about a million miles per hour. (A plasma is a gas consisting of equal numbers of positively and negatively charged particles.) This plasma wind "blows back" Earth's magnetic field into a long "tail" while compressing the field on the dayside. This shapes the magnetosphere into a huge magnetic cavity filled with large numbers of trapped particles. (If we could see the tail, it would be as impressive as any of the cometary tails we see.) The solar wind blows out as far as Neptune and beyond. The *Pioneer 10* and *11* and *Voyager 1* and *2* spacecraft are now searching for its boundary, which they are not expected to reach until the next century.

Oscillating Electrons

The aurora borealis, or northern lights, seen almost daily by people who live at high northern latitudes, such as northern Canada or Alaska, is a vivid manifestation of the magnetosphere—as is the aurora australis, or southern lights, of southern latitudes.

These trapped particles cause the aurora effect as they oscillate and plunge deep into the atmosphere, where they excite neutral atoms into radiating energy, much as the electrons hitting a television screen cause colors to appear and images to form. In addition, whenever large sunspots appear on the surface of the Sun and give rise to huge explosions called flares, the aurora fluctuates wildly and intensifies, as it did in 1989, 1990 and 1991. During those years, the aurora borealis was seen as far south as Key West, Florida.

Such "magnetic storms" disrupt electrical power distribution systems—in 1989, for example, the entire province of Quebec was without power for almost nine hours. The amount of energy deposited over the auroral zone by the particles trapped in the magnetosphere can at times exceed 1,000 billion watts, which is comparable to all the electricity produced in the world.

Another aspect of magnetospheric activity, not readily detected from the ground, is the production of radio waves. These waves are generated by electrons oscillating in Earth's magnetic field, much as electrons oscillating in a radio station's antenna generate the waves we pick up on our radio sets at

Naming the Phenomenon

As is often the case in science, a phenomenon gets a name before it is fully understood, and sometimes that name hangs on. The magnetosphere of a planet is certainly not spherical, as shown in the accompanying illustrations. But the term is still useful, conveying as it does the idea of a huge region beyond the troposphere, stratosphere and ionosphere that closely enfold our spherical Earth—a region where electromagnetic effects dominate the motions of the thin but highly energetic plasma that surrounds us. *—James D. Burke*

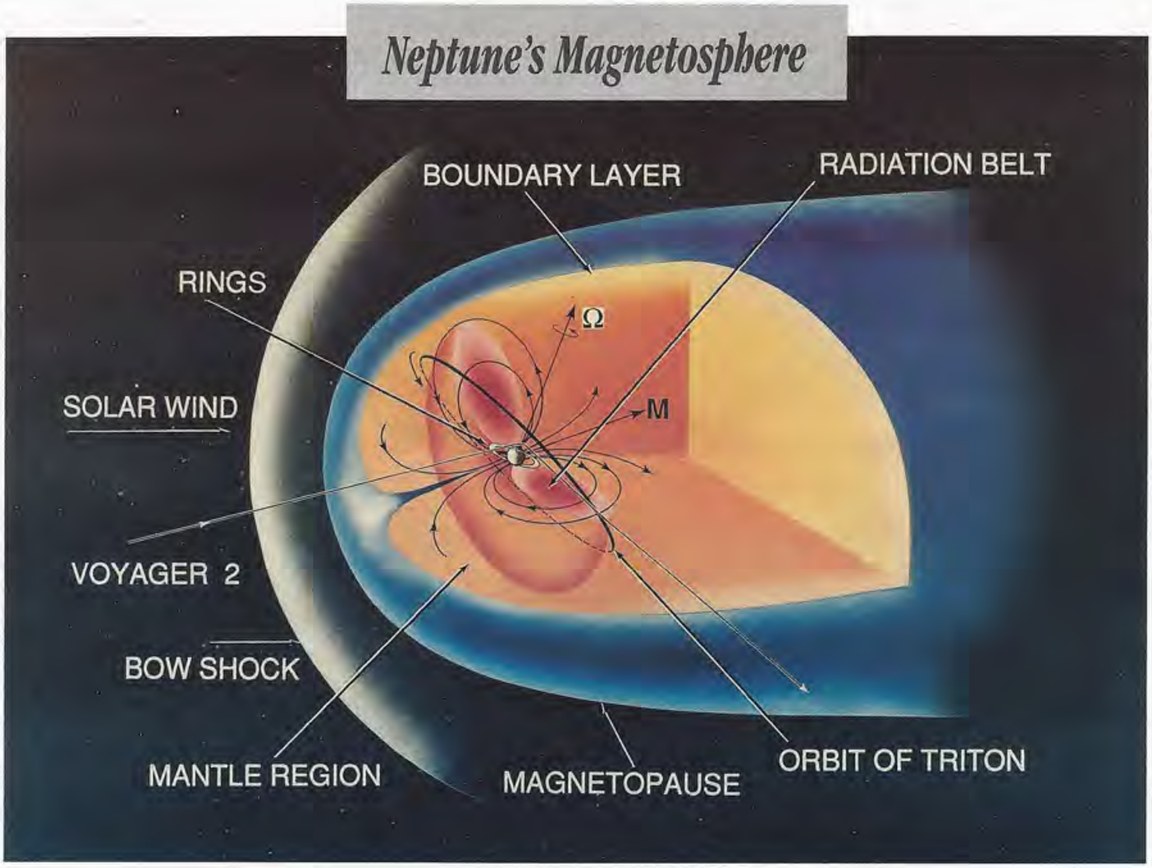


Figure 3 — Neptune's magnetosphere might have appeared something like this at the time* Voyager 2 *entered it through the south magnetic polar region. Among its prominent features are the radiation belt confined by the orbit of Triton, the compressed field on the dayside and the magnetic tail streaming out a great distance from the planet.

Illustration courtesy of S.M. Krimigis

home. They are continuously broadcast into space with the power of about 1 billion watts; by comparison, radio stations on Earth typically radiate about 50,000 watts.

Surprising Measurements

Many of the phenomena we see in Earth's magnetosphere also exist in the magnetospheres of the outer planets—Jupiter, Saturn, Uranus and Neptune. *Voyager*'s measurements at these planets, however, surprised us, both in the nature and orientation of the magnetic fields and in the extent and variety of phenomena observed. Figure 2 (page 11) compares *Voyager*'s findings with what we know of Earth's magnetic field.

An important characteristic of planetary magnetic fields is the angle between the rotation axis of each planet and the magnetic axis; this angle is approximately 11.7 degrees at Earth, 9.6 degrees at Jupiter, but 0 degrees at Saturn and nearly 60 degrees at Uranus. Note that the orientation of Uranus' rotation axis is quite different from that of the other planets, lying very close to the ecliptic plane (the plane of Earth's orbit about the Sun). Thus, the large tilt in Uranus' magnetic axis and its offset from the center of the planet were thought to be due to the peculiar orientation of its rotation axis.

At Neptune, however, *Voyager 2* found that the magnetic field was tilted some 47 degrees to the rotation axis, even though Neptune's spin axis is not tilted as drastically as is Uranus'. This was not what we expected. Furthermore, the axis of the magnetic field was displaced by over half a planetary radius from the planet's center, so that the surface strength of the neptunian magnetic field varies quite a bit depending on the longitude. Given this complexity, an ordinary magnetic compass would be useless on Neptune. The equivalent situation on Earth would have the compass pointing to, say, New York instead of the north pole.

Traversing Neptune's Magnetosphere

When *Voyager*'s antennas picked up radio waves about five days before closest approach to the planet, we knew we had detected Neptune's magnetosphere. Later examination of the data revealed that these radio "bursts" were present as early as 30 days before, and at least 22 days after, closest approach.

We used the regularity of the radio emissions to deduce the planetary rotation period of 16.11 ± 0.05 hours. This was an important measurement, for it enabled the atmospheric scientists to interpret the motions of the atmospheric features observed by *Voyager*'s imaging system.

It took *Voyager* well over three days to traverse the magnetosphere of Neptune. Putting together the measurements taken in the plasma, plasma wave and energetic particle experiments, we produced the conceptual model shown in Figure 3.

The principal features of the magnetosphere are illustrated in the figure, with the red part of the figure indicating the radiation belt-equivalent to the Van Allen belts at Earth. These belts are generally confined inside the orbit of Triton, Neptune's largest moon, in a doughnut-shaped region with Neptune at its center. There is also a cloud of hydrogen surrounding Neptune along Triton's orbit, again in the form of a doughnut.

The magnetosphere is of course distorted by the pressure of the solar wind, as we have learned to expect from Earth's and all the other magnetospheres investigated by *Voyager*. Neptune's magnetosphere extends approximately 870,000 kilometers (about 540,000 miles) on the dayside and at least 4.6 million kilometers (about 2.9 million miles) on the nightside.

Voyager found that the ionized gas trapped within Neptune's magnetic field consists of two components. One part, mostly protons and nitrogen, has temperatures ranging from about 100,000 to 200,000 degrees Celsius (about 200,000 to 400,000 degrees Fahrenheit); the other, mostly protons, has temperatures of over a billion degrees—the hottest plasma temperatures measured in any of the planetary magnetospheres encountered by *Voyager*. Since this plasma is exceedingly dilute (a few ions per cubic foot), the heat content is minuscule and therefore did not heat the spacecraft to any measurable extent.

Some of this gas finds its way to the upper atmosphere of the planet, producing an aurora, just as is the case for Earth and the other planets with sizable magnetospheres. The aurora on the dark side of Neptune is relatively weak, emitting only about 10 million watts of power, compared to emissions at Earth that range to at least 100 billion watts.

The presence of the very hot plasma has profound consequences for material embedded within the radiation belt. *Voyager*'s cameras discovered six small moons residing within this belt, as well as several neptunian rings. These inner moons and rings are very dark, and we think we know why. High-speed protons striking the surface—thought to be methane (CH_4) ice—drive off much of the hydrogen, leaving carbon behind. My colleagues L.J. Lanzerotti and A.F. Cheng estimate that it would take anywhere from 10,000 to about 1 million years for pure methane ice to assume a very dark appearance. So the moons and the rings could have been created within the last million years, just as well as at the beginning of the solar system.

The Next Frontier

Now that we have investigated all but one (Pluto) of the planets in the solar system, we can state with certainty that magnetospheres are a ubiquitous feature of rotating planets and even stellar objects, as inferred from ground-based observations of such astrophysical objects as pulsars and even entire galaxies.

The obvious question is whether the Sun itself, being a rotating, magnetized star, possesses a magnetosphere envelope in its own right. The answer is clearly yes, since we have seen that the magnetized solar wind extends beyond the orbit of Neptune, and, as of this writing, at least 8.3 billion kilometers (5.2 billion miles) from the Sun.

Thus the next challenge for both *Voyager 1* and *Voyager 2* is to cross the boundary between the magnetosphere of the Sun (called the heliosphere), and the interstellar medium, which is the space dominated by nearby suns. A hypothetical solar magnetosphere, encompassing all the planets, is shown in Figure 4. Also shown are the *Pioneer* and *Voyager* spacecraft heading toward the boundary that separates our solar system from the interstellar medium. Current estimates are that the *Voyager* spacecraft will not cross this frontier until well after the year 2000. We have to remember, however, that the *Voyager* journey has been one of surprises, and we may yet learn that our understanding of the Sun's magnetosphere is rather incomplete. Only the future will tell us the answer.

S.M. Krimigis is head of the Space Department at the Johns Hopkins University Applied Physics Laboratory, and Principal Investigator of the Low Energy Charged Particle experiment on Voyagers 1 *and* 2.

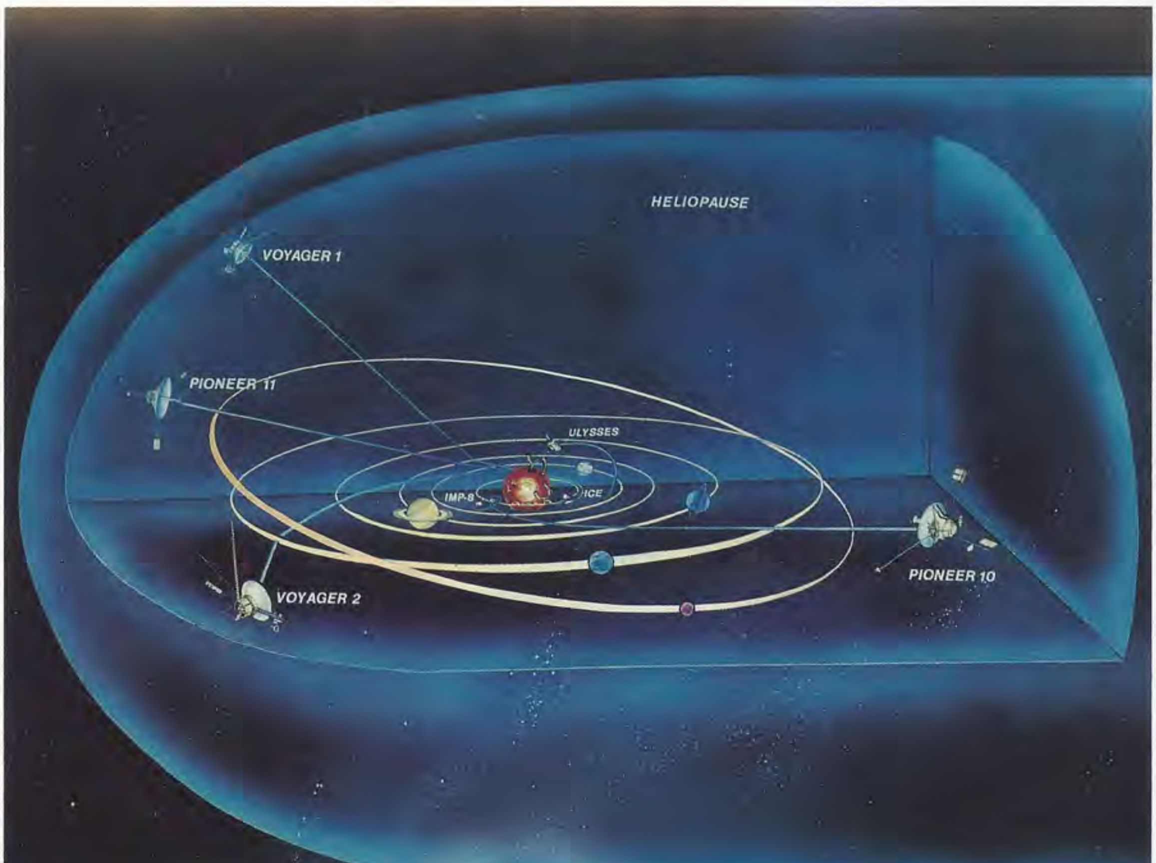


Figure 4 — The shape of the Sun's magnetosphere, the heliosphere, may resemble those of the planets investigated by* Voyager. *Four spacecraft,* Voyagers 1 *and* 2 *and* Pioneers 10 *and* 11, *are now heading out of our solar system. Sometime in the next century, one of them will cross the heliopause and enter interstellar space.

Illustration: JPL/NASA

Triton: Voyager's Finale

by R.H. Brown

It has been more than two years since I first saw Triton close up. Although I had studied that enigmatic moon through a telescope for over a decade before *Voyager 2* encountered it, in my research I have since thought of little else. Triton is one of the most amazing, perplexing and beautiful objects in our solar system. Tucked away in a strangely inclined and backward orbit around Neptune, Triton provided a finale to the *Voyager* mission that could scarcely have been imagined.

Triton represents a new class of satellite, unlike anything seen in any of the previous *Voyager* encounters. Its retrograde (east to west), inclined orbit suggests that it is a moon-sized body that got too close to Neptune. It may have been captured by Neptune's gravity after being slowed down by drag from the forming planet's tenuous outer atmosphere. In contrast to other satellites in the outer solar system, which probably formed from material in orbit around their parent planets, Triton may be representative of the kinds of objects that coalesced in large numbers to form Neptune.

After Triton's capture, its initially large and eccentric orbit slowly decayed to its present circular shape. As the orbit decayed, the moon probably suffered many catastrophic heating events that melted it and destroyed most of the surface evidence of its origins. Its present six-day orbit is inclined by about 160 degrees relative to Neptune's equator and precesses (wobbling like a spinning top), so that the pole of the orbit completes a cycle in about 690 years.

The combination of Triton's precession, Neptune's 164-year orbit and the inclination of Neptune's equator (about 29 degrees) results in a very complex seasonal cycle. In fact, Triton's southern hemisphere is presently nearing solstice in one of the longest and warmest summers it has seen in the last thousand years or so.

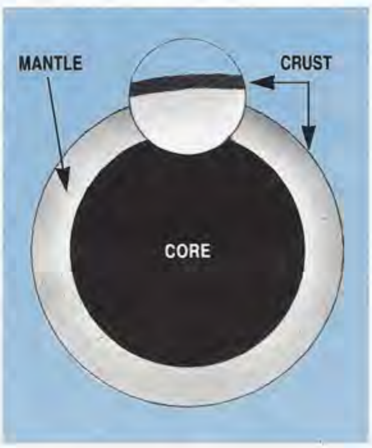


Figure 1 — In composition, Triton is about 70 percent rock and organic materials and 30 percent water ice. The rocky core is about 1,000 kilometers in diameter, while its water-ice mantle and crust are some 350 kilometers thick. A thin veneer of volatile ices, mostly nitrogen and methane, is probably no more than 1 kilometer thick.

Illustration: Ron Miller

A World of Rock and Ice

The *Voyager* measurements of Triton's mass and radius, combined with our knowledge of the behavior of common solar system materials at high pressures, tell us that Triton is quite dense, as icy moons go. At a density of 2.06 grams per cubic centimeter, over twice that of water ice, Triton must be composed predominantly of rocky and organic materials. In fact, its bulk composition is probably a mix of about 70 percent rock and organics and 30 percent water ice by mass (see Figure 1), with only minor amounts of other materials. It has the highest density of all the known moons in the outer solar system, except for the jovian satellites Io and Europa.

The predominance of rock in Triton suggests that its internal structure is differentiated—that is, its components have settled into layers. Its rocky core is about 1,000 kilometers (600 miles) in diameter, and its water-ice mantle and crust are some 350 kilometers (about 200 miles) thick combined. The surface layer of volatile ices (principally frozen nitrogen and methane) is probably no more than 1 kilometer (0.6 mile) thick.

Cold on the Outside, Warm Within

The large amount of rocky material in Triton's interior produces a substantial amount of heat from the slow decay of naturally occurring radioactive elements in the rock. Although Triton's internal heat source is not as large as that of Io, the most geologically active satellite we know of, it is quite large relative to the heat Triton receives from the Sun. This is due partly to the fact that Triton is about 4.5 billion kilometers (3 billion miles) from the Sun, and it reflects 80 to 90 percent of the sunlight that falls on its surface. As a result, at minus 235 degrees Celsius (minus 391 degrees Fahrenheit), Triton is the coldest object we know of in the solar system, aside from comets beyond the orbit of Pluto.

Even though Triton is unbelievably cold, its strong internal heat source makes its surface slightly warmer—about 0.5 to 1.5 degrees Celsius higher—than it would be otherwise. Although this may not seem like much, Triton is the only known satellite in the solar system besides Io whose internal heat source has a measurable effect on its surface temperature.

In fact, because the predominantly nitrogen atmosphere is in equilibrium with the extensive deposits of nitrogen ice on its surface, and because the pressure of a gas evaporating from a solid is very sensitive to temperature, the warming of the ice from internal heat raises Triton's atmospheric pressure by 50 to 150 percent!

Triton's high reflectivity is due primarily to the large amounts of frozen methane (CH_4) and nitrogen (N_2) on its surface. In fact, in many places on this

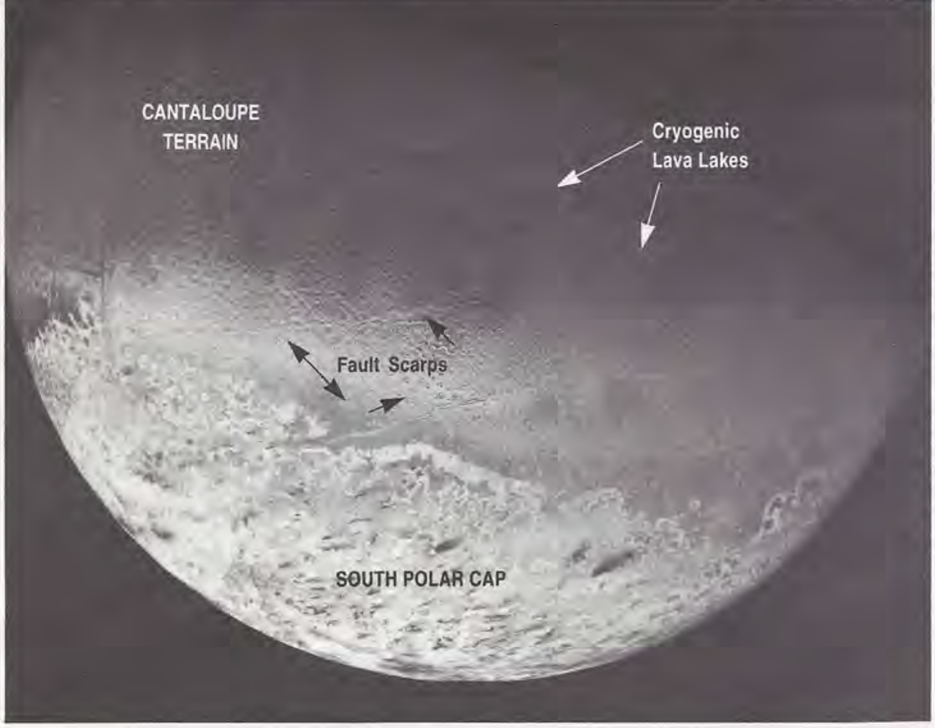


Figure 2 — Triton displays a variety of geologic features not seen anywhere else in the solar system. A vast polar cap, made of nitrogen and methane ices, dominates its appearance. Dark streaks on the bright cap are evidence of geyser-like eruptions. Triton's mid-latitudes are crisscrossed by fault scarps hundreds of kilometers long. There is the strange cantaloupe terrain, perhaps formed by ammonia–water lavas vaporizing the surface ices. Vast, cryogenic lava lakes cover hundreds of kilometers.

Image: US Geological Survey, Flagstaff

moon the reflectivities of such deposits are greater than 90 percent—as bright as or brighter than freshly fallen snow on Earth.

Frozen methane and nitrogen are not the only components of Triton's upper surface layers, however. Telescopic observations made at Mauna Kea Observatory have shown evidence for frozen carbon monoxide (CO) and carbon dioxide (CO_2). In a way similar to the way sunlight produces brownish smog from hydrocarbons in the air above many of Earth's cities, the slightly pinkish tinge we see in *Voyager* color images suggests that the action of sunlight on methane and carbon monoxide has produced small quantities of smoglike organic material.

The organic material thought to exist on Triton is probably similar to organic material on comets and dark asteroids. There probably are many other compounds on Triton, particularly simple hydrocarbons, that are currently unknown simply because they exist in quantities that are too small to detect using ground-based telescopes.

Creeping Ice and Cryogenic Lava

Sunlight on Triton, though weak, also drives a very complicated cycle of evaporation and recondensation of surface ices. Just as ordinary dry ice (frozen carbon dioxide) changes directly from a solid to a gas (a process called sublimation), nitrogen and methane ices on Triton's surface evaporate from those areas that are in full sunlight and condense in those areas where the Sun is very low in the sky. The greatest amounts of condensation are taking place in areas near the north pole that are now in total darkness and will remain so for about 40 years.

Because Triton's equatorial regions receive, on average, about twice as much sunlight as its polar regions, over time the nitrogen and methane ices are being systematically driven from the equator to the poles. There they remain, forming vast ice caps (see Figure 2).

These ice caps creep and flow in much the same way as glaciers do here on Earth. Only seasonal frost and ice deposits exist in Triton's equatorial regions, similar to the cycles of snowfall and melting that occur over much of Earth's temperate latitudes. The main difference is that winters on Triton last over 80 years, and a warm day is 390 degrees below zero Fahrenheit!

Even though Triton's south polar ice cap dominates its appearance in the *Voyager* images, on closer inspection one can find a fascinating array of geologic forms. North of the vast south polar cap lie the darker, redder regions of Triton's northern mid-latitudes.

Here the primordial coating of nitrogen and methane ices has probably evaporated away, leaving a substrate of water ice and a slag of the organic materials thought to be responsible for Triton's overall pinkish color. Here also, in the hard-as-rock water-ice crust, is evidence of the catastrophic and large-scale geologic activity that reworked Triton's face about a billion years ago.

There are vast, frozen lava lakes over 100 kilometers (60 miles) in diameter that still show evidence of the volcanic vents that gave rise to them. Although these lakes are volcanic in origin, and volcanism is a common process in the solar system, the lavas of these extinct tritonian volcanoes are fascinating, for these are cryogenic lavas—lavas that flow at temperatures where materials like water and carbon dioxide gas are frozen solid.

The material likely to have erupted from these ancient volcanoes is a thick, viscous solution of ordinary water and ammonia (although at much higher ammonia concentrations than found in household cleaning fluids). This material remains very viscous even at temperatures as low as minus 150 degrees Fahrenheit, far below the freezing point of ordinary water. Such is the stuff of some tritonian volcanoes.

Also in Triton's northern mid-latitudes are large fault scarps that are hundreds of kilometers long marking the boundaries of vast, icy tectonic plates. Although there doesn't seem to be much movement of these tectonic plates now, in the last billion years or so Triton's surface may have seen many large-scale tectonic events, or tritonquakes. These quakes would literally have torn the upper crust of Triton, leaving the complex series of intersecting ridges we see today.

The northern mid-latitudes also harbor what the *Voyager* scientists dubbed

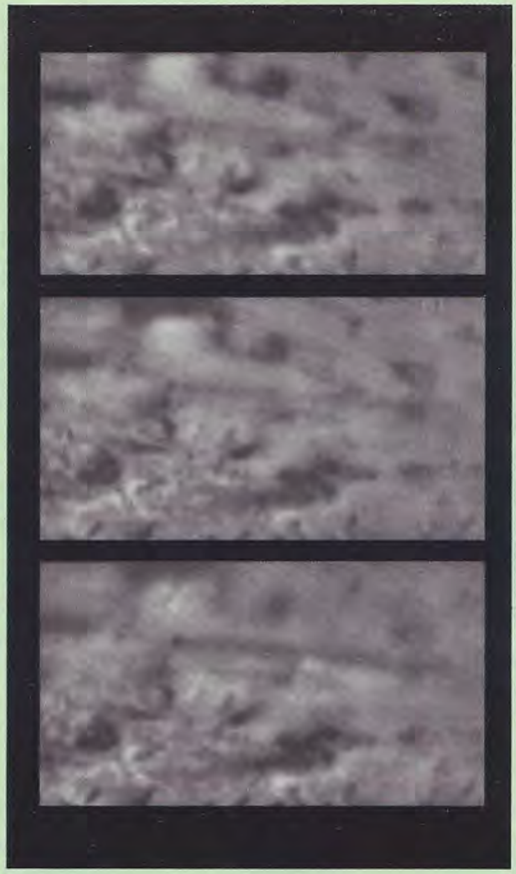
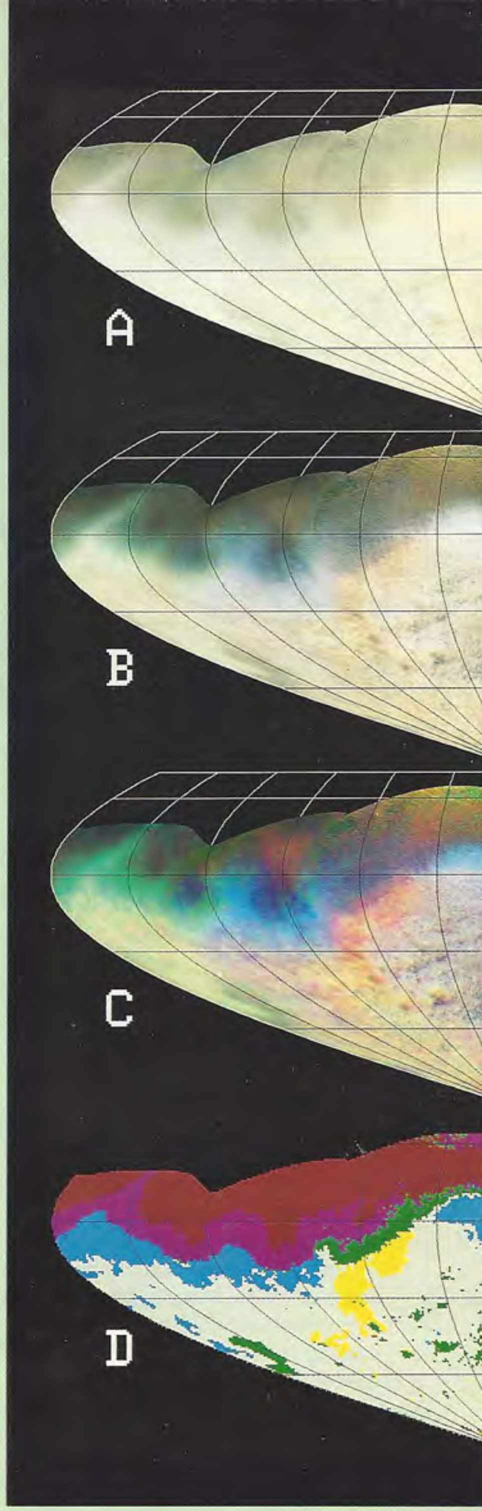


Figure 3 — Dubbed "West Plume," this dark streak (most prominent in the bottom view) is thought by some scientists to be a continuously erupting geyser of gas, ice and dust. (The dark streak appears to move from image to image due to the motion of Voyager *2 as it flew by Triton.) After rising from an 8-kilometer-high (5-mile) column, the cloud trails off to the right over 100 kilometers (60 miles). Such eruptions may be driven by the Sun shining on the nitrogen-ice surface and heating ices below, causing them to expand and burst through the surface.*

Images: Laurence Soderblom, US Geological Survey, Flagstaff



the "cantaloupe" terrain because it looks like the skin of a cantaloupe. This terrain is thought to have formed when "warm" ammonia–water lavas intruded into near-surface regions, causing surface ices such as methane and nitrogen to explosively vaporize. These explosions left hundreds of polygonal depressions many kilometers in size.

Strange, Dark Streaks

These processes, strange as they may be, still cannot top what may be the most unusual form of volcanism in the solar system. A close look at Triton reveals strange, dark streaks on the south polar cap. These streaks are reminiscent of the fan-shaped deposits called wind streaks on Mars, which are produced when winds blow dust past obstacles on the surface. But Triton's atmosphere is too thin and its winds too weak to move all but the most implausible kinds of tritonian dust particles, so another explanation is called for.

The best explanation at present seems to be that high-pressure nitrogen gas leaks through fissures in the nitrogen ice on Triton's surface, picking up dark particles and carrying them high into the atmosphere. There they are carried downwind by the gentle atmospheric circulation to settle back to the surface tens to hundreds of kilometers from the gas vent, thus leaving a characteristic streak.

But, at a temperature of minus 235 degrees Celsius, 38 degrees above absolute zero, where even gases like nitrogen are frozen solid, what could provide the energy to drive geyser-like plumes and thus produce the streaks? A clue can be found in the distribution of the streaks and in the location of geysers caught in the act of erupting when *Voyager* flew past Triton (see Figure 3).

The streaks are only found on Triton's south polar cap extending from the boundary of the cap near the equator south to latitudes of about 45 degrees where the active plumes are found. The Sun now stands directly overhead at 45 degrees south latitude on Triton, and it is there that the maximum amount of sunlight is incident on this satellite. But, as mentioned earlier, sunlight evaporates the nitrogen ice, and the gas produced quickly carries off the excess energy to areas that are receiving little or no sunlight. This keeps the surface of the nitrogen ice at a frigid minus 235 degrees Celsius, and at this temperature there is not enough gas pressure to drive the geysers.

Geysers in the Greenhouse

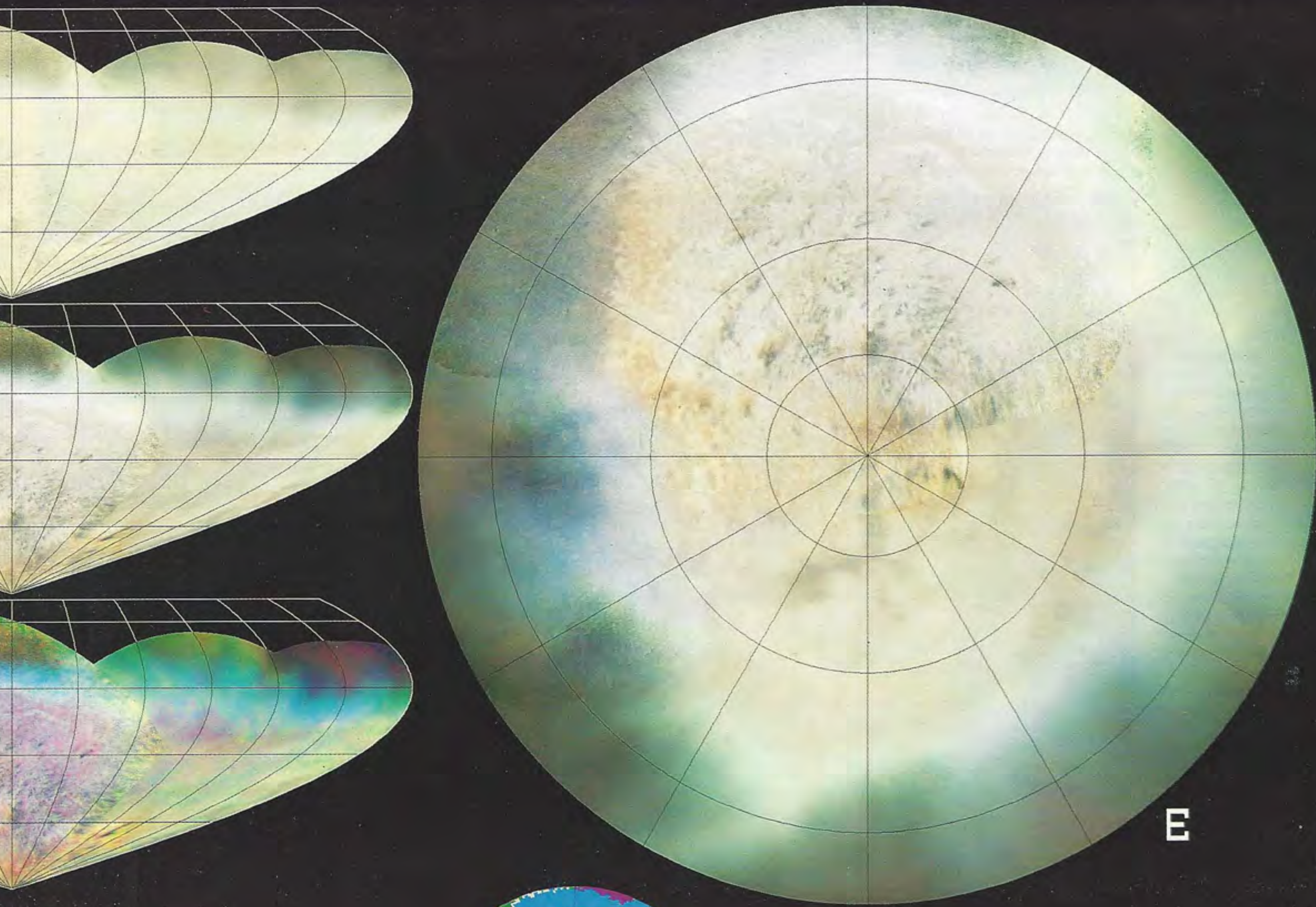
So how can temperatures and pressures build up enough on Triton to drive geysers? One way to do this is with a kind of greenhouse effect.

Imagine that on Triton's south polar cap there are kilometer-sized stretches of nitrogen ice that are relatively clear, similar to glare ice on Earth. In these clear areas, sunlight penetrates several meters below the surface, where it is gradually absorbed on the way down, heating the ice. Because frozen nitrogen is a very poor conductor of heat, the temperature several meters below the surface slowly builds up.

If these clear areas are large enough, they behave like giant solar collectors, storing energy in the form of gas pressure. When the pressure becomes high enough to break through weak places in the ice, the energy stored over a large area gets explosively released through a small fissure, and a nitrogen gas geyser erupts.

This explanation is not the only one for the geysers on Triton, however. Some scientists have proposed that the geysers are driven by heat from Triton's warm interior.

As heat leaking from the interior builds up below the nitrogen-ice polar cap, it melts the cap at its base, produc-



Voyager's television cameras transmit images to Earth as digital data containing information on brightness and color. Using computers, image processors translate the data into pictures. Mapmakers can take the process even further, producing geologic maps of the surfaces of planetary bodies. Here are several types of maps of Triton. E is a stereographic projection centered on the south pole. A is a projection showing the approximate natural color of the moon. B and E are contrast-enhanced to make surface features easier to see. C maximizes color separation, and D and F show the different geologic units.

Maps: Alfred McEwen, US Geological Survey, Flagstaff

ing geysers of liquid nitrogen as the pressurized liquid works its way to the surface and breaks through fissures in the ice cap. Although this is plausible, it may not explain why the active geysers are where the maximum amount of sunlight is falling. Perhaps the geysers are only triggered by sunlight, while deriving their main source of energy from Triton's internal heat.

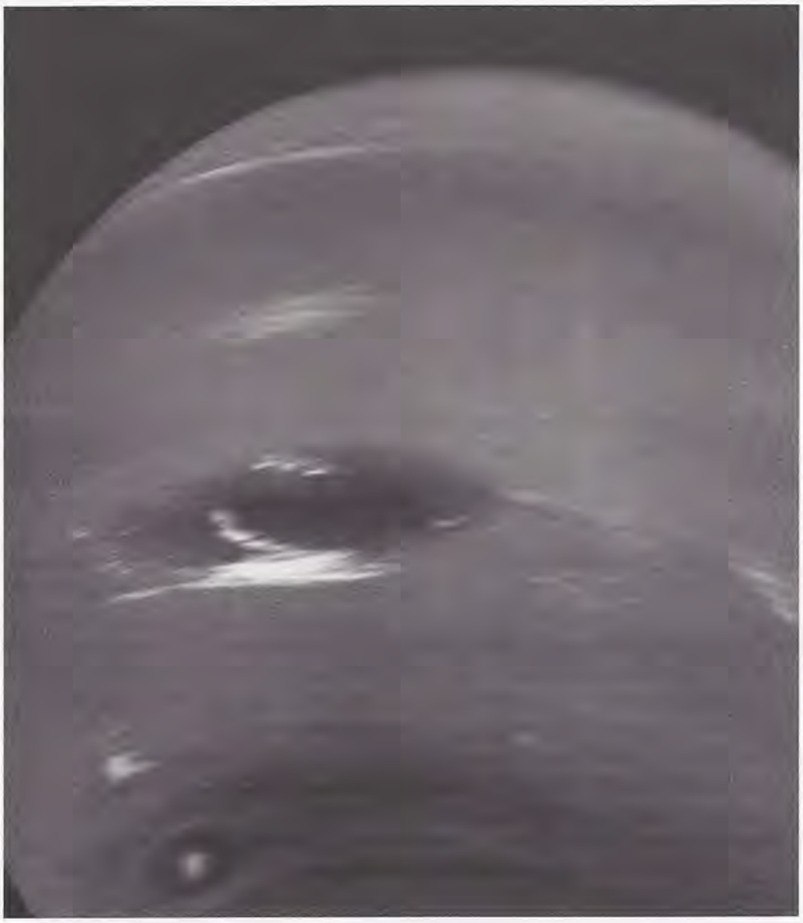
Some Answers, More Questions

Whatever the explanation, it is clear that the *Voyager* spacecraft provided us with the answers to a number of important questions about Triton. But, as has been the case with all other planetary encounters, it opened up many more new questions, some of which will be debated by planetary scientists for quite some time. Without a return to Triton, many of these questions will remain unanswered.

There is hope, however, that we may yet return to this cold and beautiful moon on the fringes of our solar system. NASA is looking into the possibility of sending a spacecraft to orbit Neptune, carrying a much better complement of instruments than did *Voyager* and returning data for more than four years. Perhaps then we will solve the vexing problem of Triton's geysers, and, in the process, learn more about the solar system as a whole.

R.H. Brown is a planetary scientist at the Jet Propulsion Laboratory.

The Clouds and Winds of Neptune



The handsome face of Neptune is distinguished by several cloud and wind features. Most prominent is the Great Dark Spot, in the center of this image, with its associated white clouds. To the lower left is the bright white feature that, in early image sequences, appeared to zip around the planet at great speed; hence its name of "Scooter." Just below that is a dark storm smaller than the Great Dark Spot, called D2.

Image: JPL/NASA

by Reta Beebe

Before *Voyager*, we knew Uranus and Neptune only as faintly bluish objects orbiting in the outer reaches of our solar system. Only one spacecraft, *Voyager 2*, has ever been sent to explore them, and we pinned many of our hopes of understanding them on this one much-traveled robot.

In January 1986, *Voyager 2* encountered Uranus, and through the spacecraft's cameras that planet's atmospheric features were, to say the least, disappointing. Its bland, blue face was shrouded by smog and revealed detail only when we computer-enhanced the images. Even then, there was little to see. As *Voyager* moved on toward Neptune, we were a little apprehensive that this world, nearly identical to Uranus in mass, would also disappoint us.

So, in August 1989, as *Voyager 2* approached Neptune and returned images of the planet across more than 4 billion kilometers (2.5 billion miles), we were astounded by the variability and beauty of the white clouds we saw against the deep blue of the planet. After *Voyager*'s disappointing encounter with smog-shrouded Uranus, these spectacular images were a welcome relief. But why should these two giant planets look so different?

The beautiful blue color of Neptune's atmosphere can be explained by the manner in which an atmosphere reflects sunlight. In this frigid atmosphere, the clouds lie at lower depths; above them, there are traces of methane gas, which absorbs red light, leaving mostly blue and green light to be reflected back toward Earth. One might conclude from this that Neptune's atmosphere has more methane than that of Uranus. But it is also possible that Neptune's atmosphere has less smog and is more transparent than that of Uranus, and we can see farther down into it, encountering more methane molecules along our line of sight. The latter possibility seems to be the best choice. Let's consider the evidence for this.

Atmospherics, Quick and Easy

The conditions in a planetary atmosphere depend on how much of the incident sunlight is being absorbed. If we carefully measure how much sunlight the planet is reflecting, we can determine how much has been absorbed. Because of Neptune's remote position in the solar system, the small amount of absorbed energy leads to temperatures of about minus 220 degrees Celsius (about minus 365 degrees Fahrenheit), and we must observe the planet in the far infrared to look for the excess heat flow from these cold clouds. When we obtain this information, we can compute the ratio of heat lost to heat absorbed. If this ratio is greater than 1, the planet must have an internal source of heat.

Early heat measurements were made from Earth-based telescopes. *Voyager*'s imaging and infrared teams refined these measurements. The results indicated that Uranus has a very small internal heat source, whereas Neptune radiates more than 2.7 times as much energy as it absorbs from the Sun. At first it seems that these two frigid planets with similar masses must differ greatly, but if we consider that the atmosphere serves as an insulating blanket through which the heat escaping from the interior must pass, we return to the idea that Neptune's atmosphere must be more transparent than that of Uranus.

The rate of heat loss from an atmosphere is governed by how opaque the atmosphere is to infrared light. If, as the infrared light emerges from the warmer interior, it is strongly absorbed by the atmosphere, the atmosphere will insulate the inner regions and reduce the outward heat flow. Small particles—such as the smog obscuring Uranus' atmosphere—absorb infrared light more efficiently. The deeper blue of Neptune's atmosphere indicates there are fewer bright particles suspended in this atmosphere to scatter the light back to us.

When solar ultraviolet light shines on methane gas (CH_4), the molecules can break apart and hydrogen atoms can escape. Through a chemical pathway involving larger hydrocarbon molecules such as ethane (C_2H_6) and acetylene (C_2H_2), small particles of smog are formed. These particles are even more efficient in sweeping up large molecules. Because Uranus is closer to the Sun, the ultraviolet light hitting Uranus is two to three times more intense than it is at Neptune, so smog forms more slowly in Neptune's atmosphere. But, since smog can accumulate over time, there must be some short-term mechanism cleaning Neptune's atmosphere.

Scrubbing Neptune's Skies

If gases circulate up from below, ices will condense onto the smog particles, increasing their mass so that they sink into the warmer regions below the clouds. There the ices melt, in the process removing smog from the upper atmosphere. If there is less smog, then the upper region of the atmosphere will be colder and the heat flow from the lower regions will be greater. A small outward heat flow will increase upwelling from below the opaque cloud deck and provide a mechanism for smog removal.

This feedback process can clean Neptune's atmosphere in a manner similar to the way that the water cycle scrubs Earth's atmosphere. The evidence that Neptune's atmosphere has more vertical mixing than that of Uranus not only explains Neptune's deficiency of smog relative to Uranus, but also suggests that individual storm centers, submerged in the deeper cloud layers, could be associated with the major cloud features that make this planet so much more interesting to view.

What *Voyager* Found

Along with Neptune's bright, white clouds, we saw distinct cloud bands encircling the planet. This indicates that strong winds may be drawing the individual clouds out into east–west streaks that coalesce to give the belted appearance. The variations in the ways the cloud bands reflect light may be due to variable amounts of white ice in the upper regions of the atmosphere. To demonstrate that this is the case, we need to track some of the distinct clouds that move with the winds. But inspection of the *Voyager* images in the weeks before nearest encounter showed white, filmy streaks, and only four well-defined features on Neptune.

The Great Dark Spot, with its associated white clouds, was the first measurable feature. Spanning a region from 8 to 28 degrees south latitude, this cloud system rotated about the planet in 18.3 hours. As the spacecraft approached the planet and we continued our search for wind tracers—clouds we could use to gauge the wind—a smaller bright spot appeared near 42 degrees south latitude. This triangular cloud rotated faster than the Great Dark Spot, passing it every eight days. Because of this behavior our imaging team dubbed the cloud "Scooter."

A third bright region occurred at 71 degrees south latitude. But as we attempted to measure its rate of motion about the planet, we found that it varied drastically in brightness from day to day. This was a clue that, in this frigid atmosphere, we were dealing with clouds that could change very quickly.

The fourth feature, near 55 degrees south latitude, looked like a dark eye with a white pupil that varied in intensity or size. This cloud moved at a rate similar to that of the Scooter. Since this was the second dark spot, we called it D2.

The radio science team announced that the period of rotation of the radio signal, presumably the rate of rotation of the planet core, was only 16.1 hours, somewhat less than pre-encounter estimates. We then realized that the Scooter was misnamed. This white cloud and D2 were not scooting eastward at high speeds. Instead, the Great Dark Spot was moving westward at more than 300 meters per second (about 670 miles per hour).

The only way that we can explain this is that, even though we found few cloud tracers, there are strong local east-to-west winds. Thus, unlike Jupiter and Saturn, which have strong eastward winds near the equator, Neptune is truly the "Planet of the Westward Wind."

A Disappearing Act

Ongoing efforts to derive wind speeds from the highly detailed *Voyager 2* images have revealed that the small white clouds change within minutes. Even at these unbelievably frigid temperatures, the clouds are condensing and evaporating before our eyes. This makes them poor markers for defining the winds. Instead, they are sensitive to local variations of pressure and temperature. Slight changes in these quantities will cause the clouds to appear and disappear.

Although these rapid changes seemed strange at first, we see similar behavior in Earth's atmosphere when air is forced to rise and flow over surface features such as mountains. As the air flows over a mountain, slight variations in the humidity cause small-scale

(continued on page 21)

Bright streaks of white clouds are a distinctive feature of Neptune's atmosphere. This image shows the clouds to the east of the Great Dark Spot and, toward the bottom, the cloud structures near the south polar region.

Image: JPL/NASA

The Nature of the Great Dark Spot

Astronomers have been observing the Great Red Spot of Jupiter since the 17th century, watching it brighten and fade, grow and shrink. When *Voyager 2* discovered Neptune's Great Dark Spot, the question immediately arose, Are these two great storms the same sort of thing?

This question is not easy to answer. With the Great Red Spot, small ammonia-ice clouds allow us to trace the winds that surround and constrain the spot. Westward winds are deflected around the equatorward side, and eastward winds flow around the poleward side of the spot. These opposing winds force the edge of the spot to rotate about its center at about 150 meters (500 feet) per second.

The Great Red Spot's east–west speed has been recorded for more than 150 years. During that time it has drifted westward at speeds of 1 to 5 meters (about 3 to 17 feet) per second relative to the planet's core. This variable speed indicates that it is a large storm that speeds up and slows down in response to its atmospheric surroundings.

Voyager infrared measurements revealed a cold region high above the Great Red Spot. This is believed to be caused by upwelling and expansive cooling of the central region of the spot. This would drive a circulation where colder material would return to lower depths around the edge of the spot. The red coloration must be due to an unidentified trace constituent in the upwelling gases that absorbs almost all the ultraviolet and blue light.

The color scheme is different at Neptune. Because methane gas absorbs red light more than it absorbs blue, if bits of white ice and smog were not present in Neptune's atmosphere to scatter the sunlight back to us, the planet would appear even darker blue. Therefore the deep blue of the center of Neptune's Great Dark Spot indicates that this is a storm center where slightly warmer smog-free gases are rising, expanding and sweeping out the overlying smog and ices.

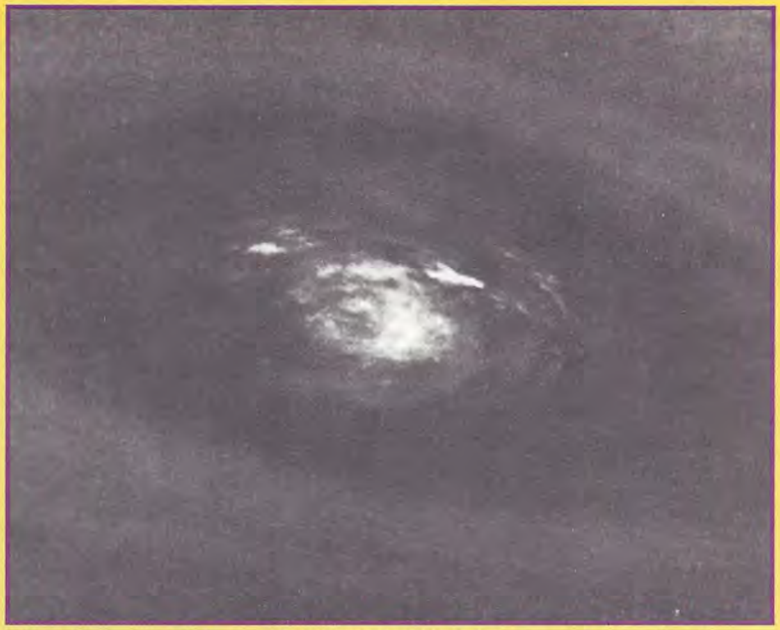
Even though this explanation seems logical, Neptune's atmosphere is not as accommodating as Jupiter's in providing us with markers to map the winds around the spot. By tracking the small white clouds we conclude that the local westward winds increase from 30 degrees south latitude toward the equator, but the extent of this change is not enough to constrain the feature into a smoothly spinning oval. Instead the Great Dark Spot appears to roll with a counterclockwise motion—looking, in time-lapse sequences, a bit like a crawling garden slug.

L.M. Polvani and J. Wisdom from the Massachusetts Institute of Technology and E. De Jong and A.P. Ingersoll from the California Institute of Technology have proposed a model for how the Great Dark Spot varies with time. Their model describes the feature as an eddy, with an upward central flow and a motion like that of an oscillating trout-fishing lure as it is pulled through a stream.

Thus, we believe that both the Great Red Spot and the Great Dark Spot are caused by local upwellings of the atmosphere. The ways in which they differ from each other are determined by how each responds to the local environment. —*RB*

***The Great Dark Spot:** The east–west dimension of the Great Dark Spot is variable, averaging about 16,000 kilometers, or 10,000 miles (the diameter of Earth is about 12,700 kilometers, or 7,900 miles). Surrounded by wispy, white clouds, it appears to be a giant eddy with clouds flowing upward in the inner regions. Carefully taken measurements of high-resolution images revealed an eastward wind along the spot's southern edge moving at about 30 meters (100 feet) per second relative to the spot. As the encroaching wind encounters the spot, the spot's internal motions deflect the air equatorward and upward. The air expands slightly and cools; white condensations of methane or ethane ice form.*

The interaction of this wind with the counterclockwise motion of the upwelling spot appears to generate the downstream wave pattern that produces the trailing clouds we see to the east of the spot.



***The Second Dark Spot, D2:** This feature appears to be a closed eddy or disturbance that is forced to roll in the prevailing winds. It is almond shaped, with a bright central area. There are no readily visible cloud markers around its perimeter. If we could determine whether the bright core is rotating in a clockwise or counterclockwise sense, it would not only permit us to infer the sense of the winds to the north and south of the feature but would also help establish whether the central region is rising from lower depths. But the central clouds refuse to be analyzed. Instead, structures in the core change rapidly, feathering out in the east–west direction as though they too are responding to an overrunning wind.*

Images: JPL/NASA

***The Bright Polar Feature:** There is an elongated white streak of clouds located at 71 degrees south latitude (at bottom in this image). Surprisingly at these frigid temperatures, this large feature varies drastically even within a day. But at high resolution we see evidence that, like the other large cloud systems, this may be a buried upwelling. Within days of closest approach,* **Voyager** *revealed small, wedge-shaped clouds moving through the large, white cloudy region at speeds of 150 meters (500 feet) per second. This indicates that the winds are sweeping material over the disturbance. Traveling at this speed, a region at this latitude, containing more than average humidity, would encircle the planet and return and brighten at the same spot within three days. This agrees in general with the variations in brightness that were observed at this latitude.*

The second dark spot, D2, appears to the west and north of the polar feature in this image.

Image: JPL/NASA

condensations. Thus, here on Earth, if we are looking at a mountain scene from a distance, we might see just a cloud over the mountain. If we fly over it in a plane and look down, we would see small regions where condensations form as the air flows over this obstacle. Beyond the mountain the air descends and warms, and the small clouds evaporate.

If there are upwellings in Neptune's atmosphere, the atmosphere would rise as it flows over these regions and white ice would form. Conversely, if there are regions where the atmosphere is descending, the ices and smog particles would melt and the amount of methane gas along our line of sight would increase as we looked more deeply into the atmosphere. This would make the atmosphere appear darker blue.

Keeping this in mind, examine the images of the Great Dark Spot, Scooter, D2 and the bright polar feature shown on these pages.

Variability Over the Long Term

During the period spanned by the *Voyager 2* observations, the Great Dark Spot drifted equatorward at a rate of 0.11 degree per day, and its westward velocity increased, indicating that it had moved into a region of increasing wind speed. D2 moved back and forth between 51 and 55 degrees, with the speed of its eastward motion decreasing as it moved toward the equator and increasing as it drifted poleward. This behavior indicates that once storm centers are generated in Neptune's atmosphere they drift north and south, responding to the local prevailing wind in a manner similar to storms on Earth. However, because the conditions on Neptune are such that the atmosphere should become denser and finally behave as a liquid, there is no solid, irregular surface. Therefore neptunian storms will not encounter the surface resistance or friction that hurricanes do when they drift inland and dissipate. Thus neptunian storms should live much longer and die less violent deaths.

During the interval from 1974 to 1984, Dale Cruikshank at Hawaii and Michael Belton at the National Optical Astronomy Observatories in Arizona observed variations in the brightness of the whole disk of the planet, indicating that the amount of white cloud structure varies with time. This and the sharp contrast between the appearance of Uranus and that of Neptune suggest that the extent of upward circulation driven by active convective cells may vary greatly with time. The atmospheres may even enter periods where there is little upward motion. Could it be that we caught Uranus in a quiescent phase and Neptune displaying active convection? Are these atmospheres not as different as our first glance would lead us to believe?

New developments of ground-based cameras sensitive to infrared light will allow us to measure variations in methane absorption that will indicate changes in the smog levels, and careful computer processing of Hubble Space Telescope images will yield some information on the fate of the Great Dark Spot during the next decade. But the limitations imposed by remote sensing, and the fascination generated by our first look at these two distant, sister planets will certainly motivate us to return with orbiting missions in the coming decades.

Reta Beebe specializes in the detailed analysis of cloud motions in the atmospheres of the outer planets. She is a professor of astronomy at New Mexico State University at Las Cruces, and was a member of the Voyager *imaging team.*

Neptune's Small Satellites

by Peter Thomas

Small satellites are not the most glamorous members of the outer planet systems. This class of objects is loosely defined as satellites of irregular shape and less than 230 kilometers (about 140 miles) in radius. Compared to the majestic planets themselves, they are mere bits of debris. They do not have the delicate beauty of ring systems. They lack the unique personalities of the larger satellites. Yet they add distinctive features to these systems. Without studying the small satellites, we cannot fully grasp the natures of the outer planet systems.

Small satellites occupy many niches in the orbital space around planets, much as do asteroids and comets orbiting the Sun. Some of these satellites orbit close to planets, often in association with rings. Some are in orbits essentially identical to those of large satellites, but ahead of or behind them by about one-sixth of an orbit. Others revolve far from planets in inclined (tilted) and even retrograde (backward) orbits. Before *Voyager 2* reached Neptune in 1989, we knew of only one small satellite in its system, Nereid. But at Jupiter, Saturn and Uranus we had discovered well over a dozen small satellites, and we expected to find more at Neptune.

Finding New Satellites

While *Voyager* was still weeks and tens of millions of kilometers from Neptune, project team members pored over its images, searching for new satellites. Nearly two months before the encounter, Steve Synnott of the navigation team found the first, Proteus (1989N1), shown in Figure 1. Images obtained over the succeeding weeks helped Bill Owen and Robin Vaughn of the navigation team to measure Proteus' orbit accurately enough to allow the team to target the high-resolution camera on the satellite near the time of encounter. During this period other new satellites appeared in the spacecraft's images, and by encounter five more had been located—Naiad, Thalassa, Despina, Galatea and Larissa (see Figure 2 and table).

To get the high-resolution images of these new worlds, the team had to know the position of each satellite relative to the spacecraft, within a few hundred kilometers. They had to work with images taken many days earlier, when the resolution was still extremely low. As was usual with the *Voyager* mission, this targeting challenge was met perfectly, and the pictures included the best resolution of any small satellite by *Voyager*, revealing details as small as 1.3 kilometers (0.8 mile) on Proteus.

Figure 1 — This is the best image Voyager 2 *took of Proteus. Its very dark surface and the speed of the spacecraft combined to limit the detail the cameras could pick out. The satellite is only about 400 kilometers across (from top to bottom in this image). A 150-kilometer crater is visible in the upper right, with smaller craters superimposed on it.*

Image: JPL/NASA

Luck was a factor in being able even to attempt this image, as the combination of the dark satellite and low light (1/900 that at Earth) meant that exposures had to be several seconds long. If the camera could not track its target during exposure, the image would be smeared. While *Voyager* had several ways to perform "image motion compensation," the limited computer memory did not permit the team to send the spacecraft additional commands to accomplish this. By chance, the spacecraft was scheduled to be turning for a radio science experiment, and the rate of motion was very close to that desired. As can be seen from Figure 1, the targeting and the motion compensation were excellent.

Characteristics of the Small Satellites

The small inner satellites are very dark, neutral in color and irregularly shaped. They reflect only about 6 percent of the sunlight falling upon them, giving them albedos (a measure of reflectivity) similar to those of some other satellites, such as Uranus' Puck, Saturn's Phoebe, and Mars' Phobos and Deimos. Such a low albedo is hard to appreciate; it is approximately that of coal. We do not know the composition of these dark surfaces or of the bulk of the satellites.

Although we expect to find ices, especially water ice, in objects at Neptune's distance from the Sun (Neptune's large satellite,Triton, apparently has a large fraction of water ice), there really is no way at present to determine the proportions of ice and rock in these satellites. Ice can be made very dark if mixed with just a small amount of dark, opaque, fine-grained material. Neptune's satellites do not show bright spots, such as those we see on Phoebe, which might be ice exposed by impacts through a dark crust. The particles that make up Neptune's rings are as dark as its small satellites—which suggests a common heritage.

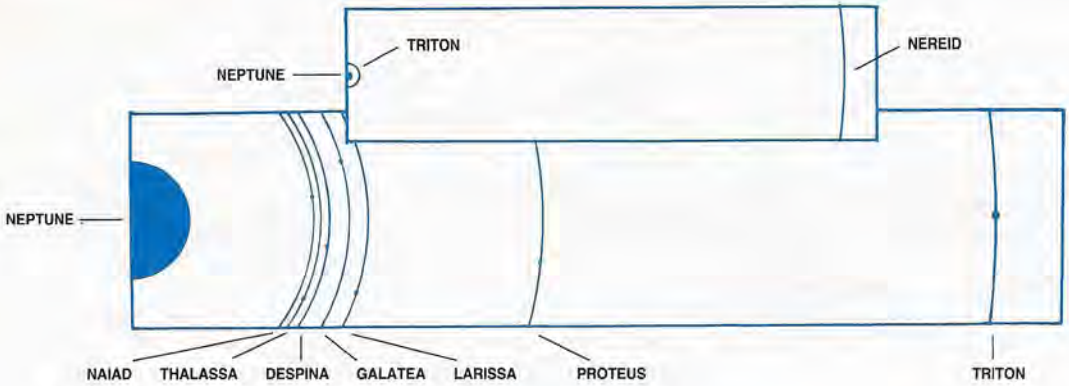


Figure 2 — The positions of the satellites of Neptune. The outermost satellites, Triton and Nereid, probably formed elsewhere in the outer solar system and were captured by Neptune's gravity. The inner satellites most likely formed in orbit. They are intimately associated with the rings, which are interspersed among their orbits.

Illustration: Ron Miller

Neptune's outermost small satellite, Nereid, is nearly three times as reflective as the inner ones. Its albedo of about 15 to 20 percent suggests that it is made of ice with a modest mixture of other materials. Its orbit and its albedo clearly differentiate it from the inner small satellites, and predominant theory is that Nereid was once wandering through the outer solar system, until it was captured by Neptune's gravity.

NEPTUNE'S SMALL SATELLITES

	Orbital Radius (thousands of kilometers)	Orbital Period (hours)	Satellite Radius (kilometers)
Nereid	5,513.4	8,643.1	170±25
Proteus	117.6	26.9	208±8
Larissa	73.6	13.3	96±7
Galatea	62.0	10.3	79±12
Despina	52.5	8.0	74±10
Thalassa	50.0	7.5	40±8
Naiad	48.0	7.1	29±6

We expect most small satellites to be irregularly shaped because they are molded by impacts that fracture and fragment them, removing and rearranging significant portions of their bodies. Because they are small, their gravities are not strong enough to smooth out the resulting irregularities in their shapes. Nor are they large enough to generate enough internal heat to trigger volcanism or the slow creep of material, which could also smooth them out.

We know that collisions are common in the neptunian system, for we have seen the cratered evidence. The two best views of Proteus (one of which is shown in Figure 1) show craters up to 150 kilometers (about 90 miles) across. Triton also has some impact craters, even though its internal activity has resurfaced much of its area.

What are the conditions on the surfaces of these objects? From their albedos we may be fairly sure that their temperatures are about minus 223 degrees Celsius, or minus 370 degrees Fahrenheit. (Brighter Triton, reflecting much more of the feeble sunlight, is even colder.) At these temperatures, water ice, carbonaceous materials, and most other materials familiar to us in solid or liquid form are extremely strong solids and would best be described as rocks.

Some of the impacts that formed the craters we see on Proteus were large enough to have fractured the satellite. This bombardment would also generate thick layers of fragmental debris, as on Earth's Moon. While some of this material may have landed as thick ejecta blankets near craters, the low gravity of these small satellites makes it likely that some material was thrown off into orbit around Neptune and then swept up again by the satellite. On Proteus, surface gravity would be about 10 centimeters per second squared (1 percent that on Earth). On Naiad, it would be only about 1.5 centimeters per second squared, and an object would take about 15 seconds to fall the height of a person, who would feel as if he or she weighed less than 1 pound.

Comparison to Other Small Satellite Systems

Voyager has shown that all four of the giant planets—Jupiter, Saturn, Uranus and Neptune—have systems of small satellites orbiting near and within ring systems. The satellites closer to the planets tend to be smaller; the largest of the small satellites orbit just outside the synchronous orbit distance, the position where a satellite's orbital period matches the rotation period of the planet.

The range of sizes of objects that are called small is substantial. Proteus, for example, has a volume about 350 times that of Naiad. There are significant differences among the systems themselves—Saturn's small satellites are bright, probably icy bodies, whereas Jupiter's inner small moons may be rocky objects covered with sulfurous material ejected from Io. The small satellites of Uranus and Neptune are approximately similar in sizes and indistinguishable in albedos.

One of the great discoveries of *Voyager* at Saturn was that small satellites act as shepherds to ring particles, confining them to narrow pathways around the planet. At Neptune, so far only Galatea has been associated with the confinement of a ring. Carolyn Porco of the University of Arizona found that it should confine the arcs in the Adams ring (see pages 4-9) to a particular distance from Neptune. The ring arcs, which appeared to be separate objects to Earth-based observers, in *Voyager*'s images turned out to be denser portions of complete rings. The positions of those clumps within the ring might also be explained by the gravitational effects of Galatea. But we have not yet found a pair of satellites shepherding the inner and outer edges of a ring, as we've seen in the saturnian and uranian systems.

We have had only a glimpse of the small satellites of the outer planets, and we have much more to learn about them. They are clearly related to the ring systems, but convincing theories on the origin and evolution of ring/satellite systems remain to be formulated. Orbiting spacecraft such as *Galileo*, now on its way to Jupiter, the planned *Cassini* mission to Saturn and the suggested Neptune orbiter may show us how small satellites relate to the rings, to the larger satellites, and to other small objects such as comets and asteroids.

Peter Thomas works at the Rand Corporation and studies surfaces and interiors of planetary satellites, as well as eolian features on Mars.

From the Editor

(continued from page 2)

Uranus? Were there clouds and storms to mark its atmospheric activity, or would it appear as bland as Uranus? Were there any satellites too small to see from Earth, waiting to be discovered?

Voyager 2 answered all these questions, taught us that in some cases we'd been asking the wrong questions, and demonstrated once again that the denizens of the solar system are stranger than we can imagine.

In this issue of *The Planetary Report*, we've asked some of the leading *Voyager* scientists to share their recent findings with Society members. These articles represent the state of our knowledge so far, but we still have not learned all the lessons *Voyager* has to teach us about Neptune, and scientists are still studying its data. This issue is probably the last special one we will publish about the *Voyager* planetary encounters, but new findings are bound to emerge from the continuing research and analysis.

And the *Voyagers* have not yet completed their mission. With *Pioneers 10* and *11*, they are heading out of our solar system. All four spacecraft are searching for the heliopause, the boundary where the solar wind of ionized particles from our Sun gives way to the wind from the stars. Who will be first to reach it?

All these spacecraft also carry messages from the people of Earth to whoever might someday encounter one of our robotic emissaries. The *Pioneers* carry plaques and the *Voyagers* golden records that commemorate the planet from which they came. Perhaps the *Voyager* spacecraft will someday encounter something even more wonderful: an alien civilization in the depths of interstellar space.

So the story of *Voyager* is not yet over. At the last press briefing of the last encounter, Project Scientist Ed Stone, who had stayed with *Voyager* throughout its epic journey, spoke for everyone when he quoted T.S. Eliot:

"Not farewell, but fare forward, voyager."

—*Charlene M. Anderson*

Three days after its last planetary encounter, Voyager 2 looked back and bade farewell to Triton (foreground) and Neptune. The spacecraft has now embarked on its interstellar mission, which will continue well into the next century.
Image: JPL/NASA

SOCIETY Notes

WASHINGTON, DC, VOLUNTEERS NEEDED

From August 29 to September 5, The Planetary Society will host 20 high-school students and their mentors from around the world. The students will be the winners of the H. Dudley Wright International "Together to Mars" contest.

Student-and-mentor pairs will be arriving at Dulles International Airport throughout the day on Saturday, August 29. We need the help of Washington-area volunteers to pick up our visitors at the airport and to take them to the Alexandria, Virginia, hotel that will lodge the group. There, a reception will be held for our volunteers and international guests.

This is a wonderful opportunity to meet young, creative space science enthusiasts from many nations. If you are able to join us in welcoming these visitors to Washington, please write to Mike Slage at The Planetary Society. *—Susan Lendroth, Manager of Events and Communications*

SEE THE MARS OBSERVER LAUNCH

The Planetary Society is planning an exciting tour of Florida to celebrate the September launch of *Mars Observer* (see the January/February 1992 *Planetary Report* for further details). For a launch tour brochure, write to me at The Planetary Society. *—Cindy Jalife, Manager of Membership Services*

ATTENTION, STUDENTS!

The 1992 Planetary Society scholarship competitions have begun! We are now accepting applications for the following:

- New Millennium Awards for high-school students, with up to $5,000 to be awarded.
- College Fellowships, with up to five $1,000 prizes available.
- The Mars Institute Contest, open to all high-school and college students, which offers a $500 prize plus a trip to a conference about Mars.

To receive an application or more information, write to The Planetary Society, Attention Scholarship Department. The deadline for completed entries is June 30. *—Carlos J. Populus, Contest Coordinator*

GENE RODDENBERRY'S LAST GIFT

A melancholy note. A few days after Gene Roddenberry's death, we received his last donation to The Planetary Society, earmarked for Project META, our radio search for extraterrestrial intelligence.

Gene had been a friend to the Society since its founding. In 1981, as we were beginning to build up our membership, he broke a long-standing rule not to let his relationship with *Star Trek* fans be used for any purpose not related to that show. Gene signed an open letter to all *Star Trek* fans recommending that they join and support The Planetary Society.

In our early days, the Society was sometimes criticized for being more interested in launching robots into space than in sending humans to explore the planets. In *The Planetary Report* (April/May 1981), Gene rose to our defense, strongly stating his belief that The Planetary Society filled the role of a broad-based organization representing all pathways toward our goals in space.

In the years since, Gene helped the Society again and again by speaking at our events and attending our fundraising dinners. Occasionally, we were able to reciprocate by offering technical advice as he developed *Star Trek: The Next Generation.*

We will miss our friend.
—Charlene M. Anderson, Director of Publications

STEPPING UP THE PACE OF DISCOVERY

Planetary Society members have just received three more dividends from their investment in our Asteroid Discovery Project. Eleanor "Glo" Helin and her team in the Planet-Crossing Asteroid Survey (PCAS) discovered the first comet of 1992, as well as two more asteroids.

On the night of January 9, Glo and her colleagues Jeff Alu and Ken Lawrence were searching with the 0.46-meter (18-inch) Schmidt telescope at Palomar Mountain Observatory. On one of their film plates, Glo and Jeff found the comet now named comet Helin-Alu (1992a) after its discoverers.

On their next observing run, the PCAS team discovered the asteroid now designated 1992BC, whose orbit crosses that of Earth, and 1992BS, which follows an orbit inside that of Earth.
—CMA

DATES SET FOR MARS ROVER TESTS

We have set the dates of May 21 to 28 for our tests of the Russian Mars Rover in Death Valley. Rover team members who have contributed to the project will soon be sent details for the test program.
—Louis D. Friedman, Executive Director

PLANETARY SUMMER SCHOOL

In June The Planetary Society and the Irvine School District will cosponsor a six-week "Planetary Academy" for students 12 to 18, to be held at the Discovery Museum of Santa Ana, California. For more information, contact Mike Slage at The Planetary Society. *—SL*

ANNUAL PLANETARY SOCIETY AUDIT

The yearly audit conducted by the firm of Stanislawski and Company has determined The Planetary Society's 1991 financial statement to be in conformity with generally accepted accounting principles. Copies of our financial statement, which includes a report on member donations restricted to special use, are available on request. *—Lu Coffing, Financial Manager*

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World Watch

by Louis D. Friedman

WASHINGTON, DC—In February, President George Bush sent his proposed budget for fiscal year 1993 to the United States Congress. It was not a good budget for the US planetary exploration program.

The Comet Rendezvous Asteroid Flyby (CRAF) mission was canceled outright. Its companion mission, *Cassini* to the saturnian system, barely survived and is still not out of the woods.

The *Magellan* mission, which has been mapping Venus so brilliantly, did not receive funds to continue operations beyond April 1993.

These actions are deplorable and constitute a major blow to US planetary exploration. The Planetary Society is strongly protesting them.

Overall, NASA's budget rose 4.5 percent to just under $15 billion. The allocation for "Space Exploration" was increased by 7 percent, but this is misleading. Several programs are grouped under this heading, and of these only the space station received an increase—of 11 percent. Planetary exploration was cut by 9 percent.

Here is a little background on items in the proposed NASA budget:

• **CRAF/*Cassini*:** CRAF was eliminated from the budget. It is possible for Congress to restore funding for the mission, but it would have to act quickly; NASA and JPL are implementing the cancellation. *Cassini* is funded for the moment, but its budget requirements for fiscal year 1994 may be a problem. (See the March/April 1987 and January/February 1989 *Planetary Reports* for mission descriptions.)

• **Life Sciences:** This item received an almost 20 percent increase for 1993. This includes NASA's project in the Search for Extraterrestrial Intelligence, which will become operational late this year.

• ***Magellan*:** The spacecraft has completed its initial radar mapping mission. By April 1993, it should have finished mapping Venus' gravitational field. Scientists had hoped to adjust its orbit to get even more detailed radar data, but no funding was provided for this. (See the November/December 1990 and May/June 1991 *Planetary Reports.*)

• **Space Exploration Initiative:** NASA Associate Administrator Michael Griffin has placed a new emphasis on robotic precursor missions for this program to send humans back to the Moon and on to Mars. The good news in this budget is that $29 million has been provided for two small and as-yet-undefined lunar missions. But mission studies were cut by 40 percent and technology for future exploration was cut by 12 percent.

The President's proposed budget will now wend its way through the congressional committee process. It will be considered, modified, debated and ultimately passed by three sets of committees: on budget, authorization and appropriations.

Can anything be done to influence Congress' action on the NASA budget? Is it worthwhile to write to members of Congress? Public support for CRAF, *Cassini, Magellan* and other exploration missions can make a difference—and may be essential to save US planetary exploration.

Special interest groups, such as the aerospace industry and professional scientific organizations, do influence the NASA budget. But the public deserves a voice in the budget, and it is up to us in The Planetary Society to provide the grass-roots support for planetary exploration that Congress needs to see.

Senator Wyche Fowler, a staunch supporter of planetary exploration, recently told me that he has received little public support for his work on the Appropriations Committee. He says that members of Congress assume that the public does not care about planetary missions.

You can prove that wrong. Let Congress know that you want the United States to keep sending spacecraft to explore other worlds.

The most important action you can take is to contact your own representatives and senators and let them know what your views are.

Your calls and letters can also be directed to these key individuals:

• Rep. Leon E. Panetta, House Budget Committee

• Rep. George Brown, House Committee on Science, Space and Technology

• Rep. Bob Traxler, Subcommittee on VA, HUD and Independent Agencies, House Appropriations Committee

All can be reached at the US House of Representatives, Washington, DC, 20515.

• Sen. Jim Sasser, Senate Budget Committee

Monitoring the Russian Mars Program

Everyone involved with the formerly Soviet space program is asking the same questions: Will the republics continue the program? Will they launch *Mars '94* and *'96*? For Planetary Society members, the question is more specific: Will they fly the Mars Balloon and the Rover?

Even though I am in almost constant contact with our Russian colleagues, I cannot answer these questions. But I am hopeful. The people with whom we work are still at their jobs and meeting their schedules. Yet this good news cannot override the uncertainty about all formerly Soviet institutions and the rampant inflation that is eating away at even fully funded programs.

We have just received extremely good news from France, a partner in the Mars Balloon project. The French Space Agency, CNES, has established a hard currency reserve of several million dollars to protect the *Mars '94* and *'96* projects.

All the spacefaring nations are having budget problems, but the fact remains that only Russia still has missions planned to land on Mars in this decade. (Ironically, their program continues while the US cancels CRAF and stops funding for *Magellan.*) This could change. We will watch the situation closely and inform our members immediately of change. —*LDF*

• Sen. Ernest F. Hollings, Senate Committee on Commerce, Science and Transportation

• Sen. Barbara Mikulski, Subcommittee on VA, HUD and Independent Agencies, Senate Appropriations Committee

All can be reached at the US Senate, Washington, DC, 20510.

WASHINGTON, DC—As we were going to press, NASA Administrator Richard Truly announced his resignation, apparently at President Bush's request.

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

As indicated in World Watch, the proposed federal budget has provoked a crisis in US planetary science and exploration. Clark R. Chapman, our faithful News & Reviews columnist, has written this opinion piece reflecting the views of many involved in NASA's planetary program. We invite other opinions and reactions.

Crisis in Planetary Science: Push Forward or Fall Back?

by Clark R. Chapman

It is 1992, the quincentennial of Columbus sailing the ocean blue and "exploration" is the theme for this International Space Year. A third of a century into the Space Age, with the Cold War behind us, we should be poised for a renewed push toward the planets, our modern cosmic ocean.

Instead President Bush's fiscal year 1993 budget would devastate planetary exploration. Many planetary scientists believe Bush would kill off planetary science to make room, within NASA's constrained budget, for a Moon/Mars-only endeavor oriented around the "Star Wars" technology of mini-spacecraft. Bush wants two new lunar orbiters that would do a fraction of what the proposed Lunar Observer could do, and would be operated by the Exploration Office of NASA (Code X), not the Space Science Office (Code S). The goal of Code X is to further the President's focused goal of sending human beings to the Moon and Mars, much narrower than the broad scientific exploration goals of Code S, which address the miracles of the universe and the lessons the study of other worlds has for understanding our own.

The Bush budget would mark the most serious retrenchment ever in United States solar system exploration. Congressional approval would create two terrible precedents:

• Cancellation of the Comet Rendezvous Asteroid Flyby (CRAF) mission would be the first time that an approved planetary flight project would be axed so far along in its development. NASA is actually closing it down before Congress has spoken. The clues asteroids and comets possess about planetary creation would remain hidden from a generation of space scientists. There is a chilling message to young scientists and engineers who might contemplate devoting their careers to a space mission: We can pull the rug out from under you!

• Turning off the *Magellan* spacecraft, which is again healthy and performing brilliantly in its Venus-mapping task, means that no matter how successful a mission is, long-term plans can be terminated and taxpayer investments wasted without warning. A tiny fraction of the $750 million already invested in *Magellan* was sought for operations in FY 1993, but Bush said no. NASA may withhold FY 1992 funds and stretch them out to delay turning *Magellan* off, but research concerning our sister planet would then suffer immediately.

Even more threatening, the president's budget book outlines the logic for terminating the *Mariner Mark II* spacecraft program, NASA's modular, phased approach to exploring the small bodies and outer planets, which had been developed in the 1980s to respond to cost constraints. Evidently, Bush's advisors tried to kill the *Cassini* Saturn mission along with CRAF until NASA's top brass objected; but the administration has signaled its intention to kill it next year.

This is a shortsighted and stupid way to run the US space program. Space exploration requires consistent long-term planning, protected from annual political/budgetary ups and downs, but Bush doesn't understand. "Think small, think less, retreat!" is the message from the White House. Imagine Queen Isabella calling out to Columbus to turn back and just explore the Azores.

NASA continues to fight fires, abrogate commitments and treat forefront research as an expendable frill. The US and Europe might collaborate on a comet sample-return mission to replace CRAF, but comet scientists are skeptical: This year's cancellations are what's real, not fanciful missions slated for the out-years on NASA's planning charts. No doubt many would-be explorers *dreamed* of sailing centuries ago, but those we remember are the ones who actually *made* the daring voyages. And the nations that prospered from exploration were those that committed to long-term investment in far-flung lands.

On Columbus' 500th anniversary, "realists" inside the Washington Beltway say there is no hope of resurrecting CRAF; we're asked to think small; and we're not supposed to anger administration officials who are fixated on the space station. But scientists and other folk who favor exploring the solar system—first by robotic spacecraft, then by astronauts—must cry out in alarm at this waste of scientific and engineering talent. Over $450 million has been invested in CRAF/*Cassini* so far ($50 million to $100 million on CRAF alone), which would be totally wasted if nothing is launched. Yet even as NASA cancels its sole mission to comets and asteroids, Bush has proposed a new asteroid mission to be done as part of "Star Wars"! Such vacillation is not what placed Columbus' name in our history books.

We should be moving out into space, not canceling and turning off excellent missions we've already invested in. Why are CRAF and *Cassini* threatened after our scientists and engineers have brought them this far along? It is partly because the space station is gobbling up NASA's limited funds while we ignore any option of using the Russians' *Mir* for our life sciences research. Also "Star Wars" militarists, having no more Soviet enemy, are turning to space as a new playground for their high-tech bombs, lasers and agile mini-spacecraft. Planetary scientists fear that Vice President Quayle's National Space Council and Bush's Office of Management and Budget may be heeding such "Star Wars" priorities. Maybe that's why they won't spend more than 3 percent of NASA's growing budget on planetary science and exploration and would thus kill approved and/or operating missions.

International Space Year is an American presidential election year. Though Bush's decisions *could* be reversed by Congress, it might be especially effective if other presidential candidates could be convinced to formulate decent space policies and get a debate going. □

Questions & Answers

Is the martian atmosphere sufficiently dense to burn up infalling material? Would a person be able to see "shooting stars" from the surface?
—Roderick S. MacDonald, Broxburn, Scotland

On Earth, most meteors "burn out" at altitudes of about 70 kilometers (about 40 miles). The atmospheric pressure there is approximately 0.1 millibar. (The standard sea level pressure is 1,013 millibars.) This same pressure level of 0.1 millibar is reached at an altitude of 40 kilometers (about 25 miles) on Mars, where the surface pressure is only 7.5 millibars. Hence these common meteors would certainly appear as "shooting stars" to an observer viewing the night sky from the martian surface, unless a martian dust storm was taking place at the time!

Given that Venus and Titan both have constant, ubiquitous "cloud" covers, and all other objects in the solar system have either very tenuous atmospheres, no atmospheres or no solid surfaces, Mars and Earth appear to be the only two bodies where meteors can be viewed in this way.
—TOBIAS OWEN, *University of Hawaii*

How do you fly into outer space?
—Cassandra Besser, age eight, Calabasas, California

The short, simple answer to your question is that we fly into outer space by going very fast. Think about it this way: If you throw a ball straight up into the air, it will rise a certain distance, then fall back. If you throw it harder (in other words, faster), it will go higher. If you throw it upward fast enough, Earth's gravity, which becomes weaker as you go higher, will no longer be strong enough to pull the ball back. Then the ball escapes into space. To es-

Two years ago, Ruben E. Lianza, then with the Argentine Air Force and now with LTV Aircraft Group in Dallas, discovered these gigantic skid marks from the air. This close-up shows the small gouge in the photo at right. The arrow points to Captain Lianza, who is standing inside the gouge. Photographs: Ruben E. Lianza

All but 2 of the 10 meteoritic gouges form a corridor about 30 kilometers (20 miles) long and 2 kilometers (about 1 mile) wide running northeast to southwest north of the Rio Cuarto, 560 kilometers (350 miles) west of Buenos Aires. The largest depression is 4.5 kilometers (3 miles) long and 1 kilometer (0.6 mile) wide. The small gouge (see arrow) is shown enlarged at left for scale.

cape Earth's gravity, an object has to go about 40,000 kilometers (25,000 miles) per hour. You and I can't throw anything that fast, but rockets can and that is why we use them to go into space.

If we want to go to the Moon or Mars, we make our rockets go fast enough to escape Earth's gravity and we make sure that we are headed in just the right direction to get to the planet we want to reach. If our aim is a little off, we fire our rockets again to correct our course.

Suppose that, rather than escaping into outer space, you want to orbit around and around Earth the way the space shuttle does. We can't do that by going straight up. Let's think about throwing the ball again. This time throw it as if you were tossing it to a friend. If you throw it at a certain speed, it will fly along a curved path for some distance before it hits the ground. If you throw it faster, it will travel along a bigger curve and hit the ground farther away. Remember that Earth is round. If you get above the atmosphere and throw the ball fast enough, the curved path it follows becomes as big as Earth and it never hits the ground. Then it is in orbit. To do that it has to go about 30,000 kilometers (18,000 miles) per hour. You and I can't throw things that fast either but, once again, rockets can and that's why the shuttle uses rockets to get into orbit.

—J.R. FRENCH, *JRF Engineering Services*

In a recent* Parade *article, Carl Sagan wrote that "the bright rings of Saturn are composed mainly of frozen water and could be described as made of snowballs or ice balls."

I remember reading that if Saturn's rings were made mainly of ice and were as old as they are said to be, the ice would, by this time, have disappeared by sublimation.

—Bolton Davidheiser, La Mirada, California

The very bright ring particles of Saturn are almost pure water ice, although their slightly orange-brown color shows that they must contain some other material, such as silicates or primitive organic material. The amount of non-icy material may be as small as 1 percent. Saturn's rings are unique in their brightness; the ring particles of Jupiter, Uranus and Neptune are very dark, containing a substantial amount of the rocky and/or carbonaceous material that is abundant in asteroids and comets.

The stability of Saturn's rings despite a long list of rapid removal processes has become a major area of study. Ironically, sublimation, which was one of the first processes suggested, is probably not important because of the very low evaporation rate of water ice at the frigid temperatures of the outer solar system. However, several other processes lead to "short time-scale problems" (survival times much shorter than the age of the solar system) with all known ring systems:

1. Incessant meteoroid bombardment tosses chips and dust all around the rings. Most of these merely land elsewhere in the rings, but each impact vaporizes some fraction of ring material and this might fall into the planet.

2. The rings may absorb enough meteoroid mass to "weigh them down" and cause them to fall into their planets in 10 million to 100 million years.

3. Because meteoroid material is dark (remember Halley's Comet), the large amount of this being mixed in with ring material makes it very hard to understand how Saturn's bright rings could remain so "clean" unless they are less than 100 million years old.

4. Gravitational interactions between rings and their nearby shepherding satellites cause spiral density waves much like those seen in galaxies. These interactions are thought to cause the rings and satellites to evolve away from their current locations in a similarly short time.

Because these processes affect all ring systems, many scientists now believe that rings are transient phenomena. They must be recreated sporadically over the aeons when moons are destroyed by unusually large impacts. The *Cassini* orbiter currently being planned by NASA and the European Space Agency will make measurements that allow us to determine the age of Saturn's rings and establish how they were created.

—JEFFREY N. CUZZI, *NASA Ames Research Center*

FACTINOS

Alexander Wolszczan of Cornell University's National Astronomy and Ionosphere Center and Dale A. Frail of the National Radio Astronomy Observatory in Socorro, New Mexico, have found what they think is the first definitive evidence of planets orbiting a star outside our solar system.

The researchers used the Arecibo radio telescope in Puerto Rico to take precise timing measurements from the recently discovered pulsar PSR1257+12. They noticed a tiny "wobble" that could be caused by orbiting planet-sized bodies.

The two planets detected so far are 2.8 and 3.4 times the mass of Earth. Their respective distances from the pulsar are 0.47 and 0.36 astronomical unit (the distance between Earth and the Sun, about 150 million kilometers), and they move in almost circular orbits with periods of 98.2 and 66.6 days.
—from *Nature*

❖

Andrew Lyne of the University of Manchester's Nuffield Radio Astronomy Laboratories in England now reports that the discovery he announced last July of a planet orbiting a distant pulsar has turned out to be erroneous. (See the September/October 1991 *Planetary Report.*)

"The planet just evaporated," he said, because changes in signals from a distant pulsar —which he and some colleagues thought were caused by a planet revolving around the pulsar—turned out to be caused by Earth revolving around the Sun instead.

However, Alexander Wolszczan said Lyne's misfortune "does not change my thinking about what I have found." Other experts who have examined Wolszczan's data hailed his evidence as the best yet of other planets.
—from the *Los Angeles Times*

❖

The explosion of a giant meteorite as it grazed Earth less than 10,000 years ago gouged a chain of elongated depressions in the Argentine pampas, scientists say.

The energy released by the meteorite, which was 150 to 300 meters (500 to 1,000 feet) in diameter, appears to have been equivalent to the explosion of 350 million tons of TNT. This is 30 times larger than the energy thought to have been released in 1908 by the explosion of a mysterious object over Tunguska in Siberia.

Laboratory tests show that the object approached Earth at an angle of less than 7 degrees. Peter H. Schultz of Brown University, one of the scientists investigating the event, said that it exploded as it did so, gouging the landscape.
—from Walter Sullivan in
The New York Times

Worlds of Wonders

Contact Lithograph

A limited-edition lithograph of the art created for the cover of Carl Sagan's novel about first contact with extraterrestrials. The painting shows Earth looming on the outskirts of a distant galaxy. Artist Jon Lomberg has produced only 950 of these prints, each signed and numbered. Must be shipped TNT Air outside the United States.
19" x 24". 2 lb.
#306 . . . . $48.00

Hugg-A-Planet Earth

Curl up with Mother Earth. This colorful, 14-inch-diameter pillow of our home planet is a fun way to brush up on geography. It's great for resting or just tossing around. Place one on the sofa to add a global touch to your decor. 3 lb.
#526 . . . . $15.00

Asteroid Belt School of Mining Sweatshirt

Asteroids could be an important source of metals and minerals. Who will have the job of tapping this resource in our future? Why, graduates of the Asteroid Belt School of Mining, of course! This distinctive design displays black lettering on a white 50/50 cotton/poly blend sweatshirt. Sizes S, M, L, XL. 1 lb.
#600 . . . . $21.00

Mars Tech Sweatshirt

Wear the shirt that's sure to be a "must" with the class of 2092! Our 50/50 cotton/poly blend sweatshirt will keep you warm and comfortable on those brisk spring mornings, while showing your allegiance to old Mars Tech/ Deimos campus — the most far out university in the solar system.
Sizes S, M, L, XL. 1 lb.
#631 . . . . $21.00

Book, Books, Books

The Planetary Society offers a wide range of books on planetary science and space exploration. Here is a selection of just four of them: The *Peterson First Guide to the Solar System*, by Jay M. Pasachoff, is an in-depth examination of our solar system, suitable for both beginning and knowledgeable observers. *In the Stream of Stars* represents a joint venture by Russian and American space artists. Edited by William K. Hartmann, Andrei Sokolov, Ron Miller and Vitaly Myagkov, it presents full-color reproductions of nearly 200 paintings from art workshops sponsored by The Planetary Society. *The New Solar System*, edited by J. Kelly Beatty and Andrew Chaikin, has become a standard reference work on our solar system. *Wanderers in Space*, by Kenneth R. Lang and Charles A. Whitney, presents the results of spacecraft missions throughout our solar system.

Peterson First Guide to the Solar System	218 pages	1 lb.	**#101 . . . . $4.50**
In the Stream of Stars	183 pages	4 lb.	**#124 . . . . $27.00**
The New Solar System	326 pages	4 lb.	**#180 . . . . $22.50**
Wanderers in Space	316 pages	3 lb.	**#197 . . . . $24.00**

A Planetary Miscellany

Exploring the Universe 1992 Calendar

Produced by the creators of *Astronomy* magazine in cooperation with The Planetary Society. Each month features a striking full-color photograph or painting, and notes dates important to the history of space science. Columns of text cover subjects ranging from supernova 1987A to Isaac Newton's conception of universal gravitation. "The Planets This Month" feature offers viewing information. 2 lb.
#520 .... Special offer! Was $8.00, now $4.00

Mars Balloon Wristwatch

Be timely in your support of the Society's Mars Balloon project. This quartz wristwatch sports a white analog dial showing the Mars Balloon floating above the planet's surface.
Please specify black or white. 1 lb.
#535 .... **$20.00**

Mission Stamps

Add a distinctive touch to your correspondence while you show your support for The Planetary Society! These decorative stickers feature spacecraft for missions to Mars, Jupiter and Venus, with the Society's name and address. 10 sets (4 stamps per set) per order. 1 lb.
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Dive Europa T-Shirt

Why "Dive Europa"? This moon of Jupiter may conceal a vast global ocean beneath its cracked, icy surface. In the distant future explorers may use special diving gear to help unlock the secrets of this world, and even search for water-based life.
100% cotton. Sizes M, L, XL. 1 lb.
#568 .... **$14.00**

The Universe

Explore planets and pulsars, quasars and black holes; relive the birth of the universe and more. 30 min. videocassette. 2 lb.
VHS (US) #440, PAL (VHS-Europe) #442 .... $25.00

Solar System Exploration

This 30" x 35", full-color poster outlines human achievements in space, depicting the solar system and some of the spacecraft that have explored it. Comes with a 30-page guide. 2 lb.
#334 .... **$11.00**

Note: Although we have fewer items listed here this month, most of the merchandise that has appeared in previous issues of *The Planetary Report* is still available. For a complete list of items, please call 1-818-793-1675.

Jupiter/Saturn/Uranus Poster Set

Three full-color posters depict Jupiter with the Galilean satellites, Saturn with six of its moons and Uranus with its five largest moons.
Each 22½" x 29". 1 lb.
#327 .... **$15.00**

Solar System in Pictures

Decorate your home or office with these views of the solar system. All nine planets are featured on full-color, 8" x 10" mini-posters. Each includes vital statistics and a scientific description of the planet. 1 lb.
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The Planetary Report Binder

Protect your copies of *The Planetary Report* while keeping them handy for future reference. Our handsome blue-and-gold binder will hold two years' worth of issues. 2 lb.
#545 .... **$10.00**
Two binders (4 lb.) for $18.00!

Earth From Space

Taken by the *Apollo* astronauts, the full-disk image of Earth used for this laser print offers a striking view of our home planet.
16" x 20". Full color. 2 lb.
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Night Star

Your complete guide to the whereabouts of all 88 constellations and the major planets. Perfect for the beginning stargazer, and popular with amateur and professional astronomers worldwide. Comes with a clearly written activities handbook, three helpful accessories and a one-year warranty. 2 lb.
#548 .... **$45.00**

On Robot Wings — A Flight Through the Solar System

Take a trip to the outer reaches of the solar system—without leaving your living room. Produced by the Jet Propulsion Laboratory to assist in the study of terrains, this collection of six short video clips uses computer-generated graphics to simulate low-altitude flight through three-dimensional landscapes.
Approx. 35 min. videocassette. 2 lb.
VHS (US) #420, PAL (VHS-Europe) #422 ... $25.00

Hugg-A-Planet Mars

Created in approximate scale with Hugg-A-Planet Earth. Like its sister planet, this 8-inch-diameter pillow is both educational and fun. Learn about the features of Mars' surface while you indulge in a game of planet-toss! 1 lb.
#528 ...... Special offer! Was $13.50, now $10.00

The Planetary Society Pencils

Our bright, metallic-finish pencils are great for school, home or work. Set of 10. 1 lb.
#675 .... **$4.00**

Neptune Poster Set

These two 22½" x 29" posters were produced from images transmitted by *Voyager 2*. A full-disk picture of Neptune features the Great Dark Spot and high white clouds of methane. A mosaic of Triton, Neptune's largest moon, shows the widely varied terrain, extensive nitrogen ice cap and evidence of active geysers. 1 lb.
#331 .... **$10.00**

An Explorer's Guide to Mars

This 40" x 26", full-color poster surrounds a central map of Mars' surface with photos, paintings, polar projections and images taken by *Viking* spacecraft. Text presents brief discussions of the planet's canyons, winds, volcanoes and more. 1 lb.
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Milky Way Galaxy Lithograph

From *Cosmos* by Carl Sagan, this lithograph of a painting by Jon Lomberg depicts the galaxy from slightly above the spiral arms, with the older and redder galactic core in the distance. From a limited edition of 950, each print signed and numbered. Must be shipped TNT Air outside the United States. 17" x 24". 2 lb.
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Officers of The Planetary Society contribute to the Society the royalties due them as authors of the books advertised in these pages.

SUNLIGHT AND ICE ON TRITON — An icy peak on Triton serves as a prism for sunlight in this fanciful painting. With a surface temperature of minus 235 degrees Celsius (minus 391 degrees Fahrenheit), this mysterious world of ices is the coldest object ever measured in our solar system. As Uranus' Miranda did in 1986, this moon of Neptune stole a large part of the show during the 1989 encounter with Voyager 2.

Space artist Arthur Gilbert lives and works in the United Kingdom. He is a member of the International Association for the Astronomical Arts, and his work has appeared in the Smithsonian's National Air and Space Museum and in Space World *and* Ad Astra *magazines.*

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