The PLANETARY REPORT

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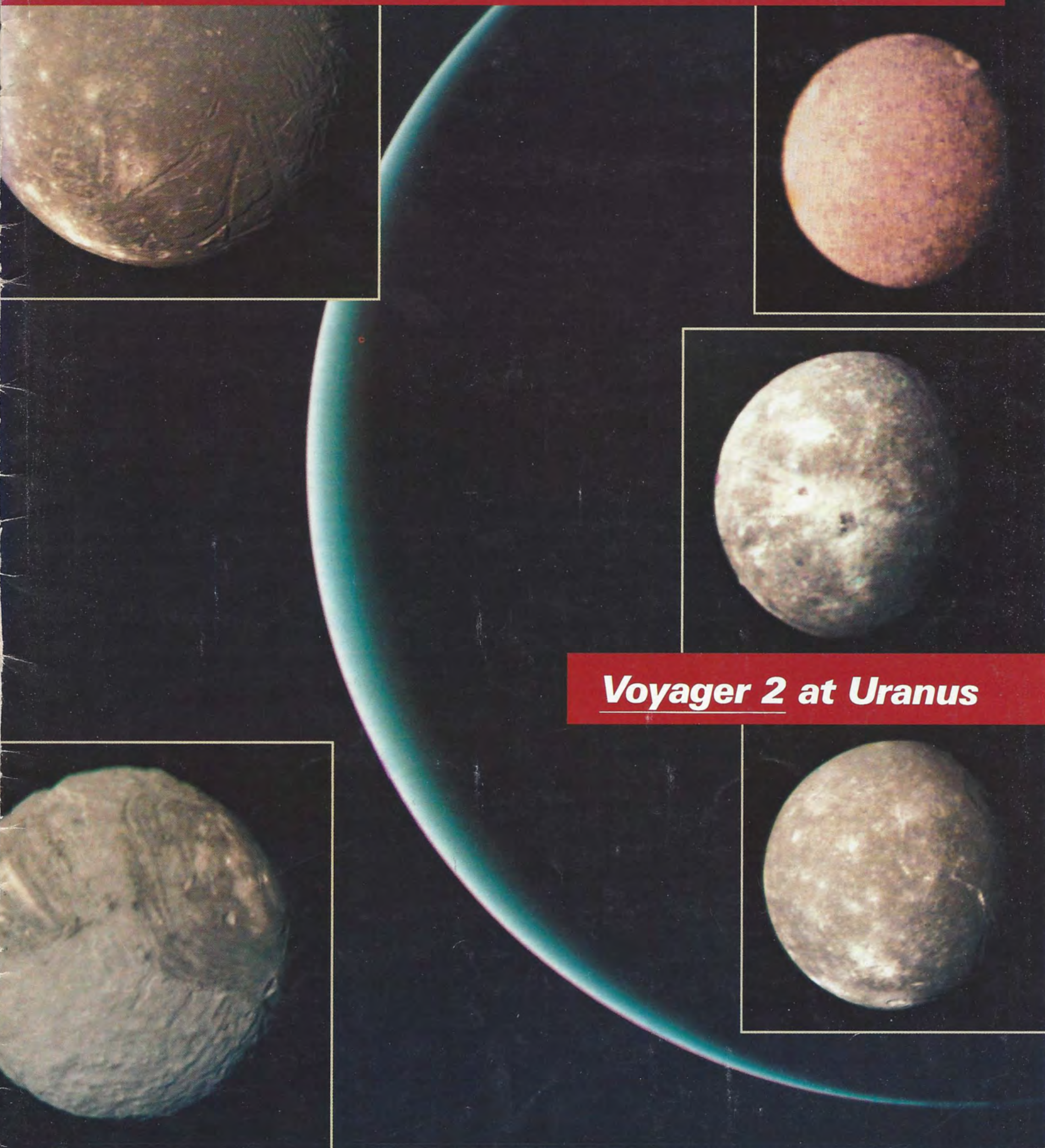

Voyager 2 at Uranus

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COVER: The thin crescent of blue Uranus is surrounded by its five major satellites in this montage created from images returned by Voyager 2 during its January 1986 encounter with the uranian system. The satellites are, clockwise from top left: Ariel, Umbriel, Oberon, Titania and Miranda. Voyager 2 discovered ten smaller satellites orbiting between the planet and Miranda, the innermost large satellite. *Images: JPL/NASA*

Letters to the Editor

We encourage our members to write us on topics related to the goals of The Planetary Society: continuing planetary exploration and the search for extraterrestrial life. Letters for publication should be short and to the point. Address them to: Letters to the Editor, P.O. Box 91687, Pasadena, CA 91109.

I would like to express my appreciation to Eleanor Helin for allowing the members of The Planetary Society to name asteroid (3129) 1979MK2. Needless to say, I was very pleased to learn that my suggestion of "Bonestell" was selected.

I have been fascinated by Chesley Bonestell's art ever since I was old enough to reach *The Conquest of Space* on my father's bookcase. Many other people, whose interest in space was kindled or enhanced by his art, would play a major role in making space travel a reality. Few artists, if any, have affected the future as greatly and as positively as Mr. Bonestell did.

In the 19th century, landscape artists depicted the great American west and inspired pioneers to embark on voyages of exploration and settlement. Today, space artists serve the same role for our new frontier.

RONALD PALUDAN, *Tuscon, Arizona*

The Planetary Society greatly mourns the passing of Chesley Bonestell, who died June 11, 1986 at his home in Carmel, California. The Society staff would like to thank Mr. Paludan for suggesting the name "Bonestell" for asteroid (3129) 1979MK2. Mr. Bonestell's obvious delight in his asteroid touched us all; we felt a rare pleasure in being able to honor him in his lifetime. — Editor

I feel that a major goal in the US space program should be to put spacecraft in orbit about each of the outer planets. It may be possible to construct a generic spacecraft to achieve these goals. With our experience from the *Voyager* flybys, we may be able to gain much additional knowledge from such an orbiter program.

ROALD STEEN, *Woodbury, Minnesota*

Several ideas occurred to me while reading the report of the Rogers commission. I do not feel that commercial space ventures are NASA's strong point. They work much better with a scientific goal. Let an American company get into the space launch business. NASA could use the shuttle flights that would have been used for commercial purposes to build the international space station and for planetary missions or other shuttle-specific work.

With the pressure of economy off, NASA could concentrate on new scientific endeavors that would return the United States to leadership in space. This is a nation that pioneered space and it would be a shame to let that lead slip through our fingers because we could not face the simple truth. NASA was set up for scientific goals, not to be the low-cost supplier of space access.

RANDALL S. LUHMAN, *Tulsa, Oklahoma*

I have noted that you favor a mission to Mars. Being a sanitary engineer, health physicist, industrial hygenist and toxicologist, I would oppose any such frivolity. We are not able to control our environment here on Earth. We generate more trash than any other nation and are rapidly making the United States into a trash dump. Perhaps we could devise a plan to send the trash to the Moon rather than spend money to go to Mars!

I realize that we should always look to the future, but this Mars business is asinine. We should continue to obtain scientific data from our shuttle endeavors and use it to our advantage.

WILLIAM H. AAROE, *Charleston, West Virginia*

Sir William Herschel Discovers Uranus

On January 24, 1986, The Planetary Society held a symposium at the California Institute of Technology to commemorate Voyager 2's encounter with Uranus. There, Dr. Michael Hoskin, a distinguished historian of science from Cambridge University, delivered the following talk in which he took on the persona of Sir William Herschel, the discoverer of Uranus.

LADIES AND GENTLEMEN, WE HAVE SEEN SEVERAL near miracles performed in the last few hours, and probably will see more tomorrow, but one miracle the organizers haven't been able to perform is to resurrect Sir William Herschel. They would very much have liked to invite him here today, but I am here as the next best thing. If you will allow me, I will stop speaking as myself and say what I think William Herschel might have said if he had lived long enough to be here:

First, Mr. Moderator, I would like to complain about the name you are giving my planet. The Astronomer Royal invited me, as the discoverer, to assign a name, and I did so in honor of our sovereign king, George III. I call it the Georgian Star just as Galileo, long ago, called the moons of Jupiter the Medician Stars. I hope that for the rest of this meeting, sir, the Georgian Star will be given its proper name.

Now, you brought me here to tell you something about how I discovered this planet. I remember the evening vividly, though in many ways it was a routine day. I'd been teaching music to several pupils; I'd put the finishing touches on a symphony and in the evening I went to the garden of my home in King Street in Bath. I got out the telescope I'd built a few years earlier.

The success of the evening came about because, if I may modestly put it, sir, I'm the only person in history to have the three talents needed to make a truly universal astronomer: First, at the time in question, one needed the skills of a telescope maker to make a really excellent telescope for oneself. Second, one needed dedication and perseverance as an observer. Third, one needed the interest and intellectual commitment to speculate on what one had observed. I like to think that I was the only astronomer in history who had all these talents to a high degree. (Modesty is, as you know, a characteristic feature of astronomers.)

I was so good at observing that when I looked at this area of sky I noticed in an instant that this particular star had a little disk, unlike all the others. Now, the Astronomer Royal and the Professor of Astronomy at Oxford, when I told them roughly where to look — I didn't know enough astronomy to tell them exactly where to look — they had the devil's own job because all they could see was a whole lot of stars.

Some of you will think I was lucky to find it. It's true. I wasn't looking for a planet. I was, in fact, studying every star down to a certain magnitude systematically, one by one. Sooner or later the turn of this object had to come.

Now why would I, or any sane person, examine each star? Well, my interests were in the universe at large, in the construction of the heavens, as I like to call it, and not just in the planets. I wanted to discover how far away the nearest stars are. The obvious way to do this was by seeing how much the stars move as we on Earth move around the Sun — the annual parallax. But where astronomers with fixed instruments might measure the actual angle and position of a star, I had no hope of doing that because my instruments weren't carefully mounted. I just moved around and pointed them roughly in the right direction.

But Galileo had given me a clue: He suggested that, if I could find a couple of stars almost exactly in the same line of sight, and if one of these stars was a very distant one, then that star might be a kind of fixed point, providentially provided by nature, against which I would observe the apparent movement of the other, nearer star. So I was looking for apparent double stars — two stars so close together that, at first sight, they appear to be one. That's why I was looking at each star carefully to see if it were single or double. So when I came to the Georgian Star, I realized it was something special.

Now you might wonder how I came to be that evening in this curious situation — a musician out studying stars one by one. Well, I was born in 1738 in Hanover and I followed my father into the regimental band of the Hanoverian Guards. But I'm afraid the Hanoverian Guards didn't do too well in the Seven Years' War. I spent an uncomfortable evening in a ditch alongside my father with cannonballs flying overhead. Dad said to me, "Why don't you get the hell out of this?" So I did.

I went to England to earn a living in music. I hit the jackpot in 1766 when I became the organist at the Octagon Chapel in Bath. Bath was the Las Vegas of England in that day. This post gave me a comfortable existence. After a few years I wanted to enlarge my interests beyond music and I began studying the mathematical theory of harmonics in the book by Professor Robert Smith of Cambridge. This led me to Smith's *Optics*, which told me how to build telescopes and what to see with them. Then this led me to Ferguson's *Astronomy*, which again told me more about astronomy. And so I was launched.

From the start, my commitment was to understand the construction of the heavens. When I discovered this planet, which I thought at the time was either a nebulous star or a comet, it never occurred to me that it might be a planet. I didn't have the skills to determine its orbit or distance — these quantitative matters were quite beyond my grasp. So I was happy to turn it over to the professional astronomers.

When I look back, I wonder what was the real importance of my discovery. It was this: My friends were able to say to the King, "Look, you've got this famous astronomer in your dominion and he's having to spend all his time teaching kids to play the fiddle. Shouldn't you do something about it?" And the King did. He said that if I would live near Windsor Castle, just to show the Royal Family the heavens on the rare occasions when they wanted to see them (and, you remember, the King went mad, so the duties proved fairly light), then I would have a pension for life and total freedom to give myself to astronomy.

I collected 2,500 nebulae, some 800 double stars, and long catalogs of the comparative brightnesses of stars. I studied which way the solar system was moving in space. I showed that binary stars are bound together by gravity — the first proof that gravity extended beyond the solar system. I studied the evolution of galaxies and the nature of cosmology. When I began, astronomy consisted of the study of the solar system against a fixed backcloth of stars. When I finished, astronomy was the study of the universe as a whole. This, I think, is the real legacy of my discovery of the Georgian Star. □

Exploring the U

When *Voyager 2* arrived at Uranus on January 25, 1986, most of us on the project were unprepared for what we saw, even though in the 10 years before the flyby we had made important advances in our knowledge of the uranian satellites. Many on the *Voyager* Imaging Team, including me, expected that these satellites might not be as interesting as the moons of Jupiter and Saturn. If, as we thought, the uranian satellites were battered, long-dead relics of the titanic forces that formed Uranus, they might not teach us much.

Experience with other *Voyager* encounters should have taught us that our expectations might be wrong. As has become the rule, *Voyager* surprised, delighted and perplexed us when it returned its treasure trove of images of the uranian system. The spry old spacecraft discovered 10 new satellites and returned breathtaking close-ups of the five known satellites — new worlds to understand and appreciate.

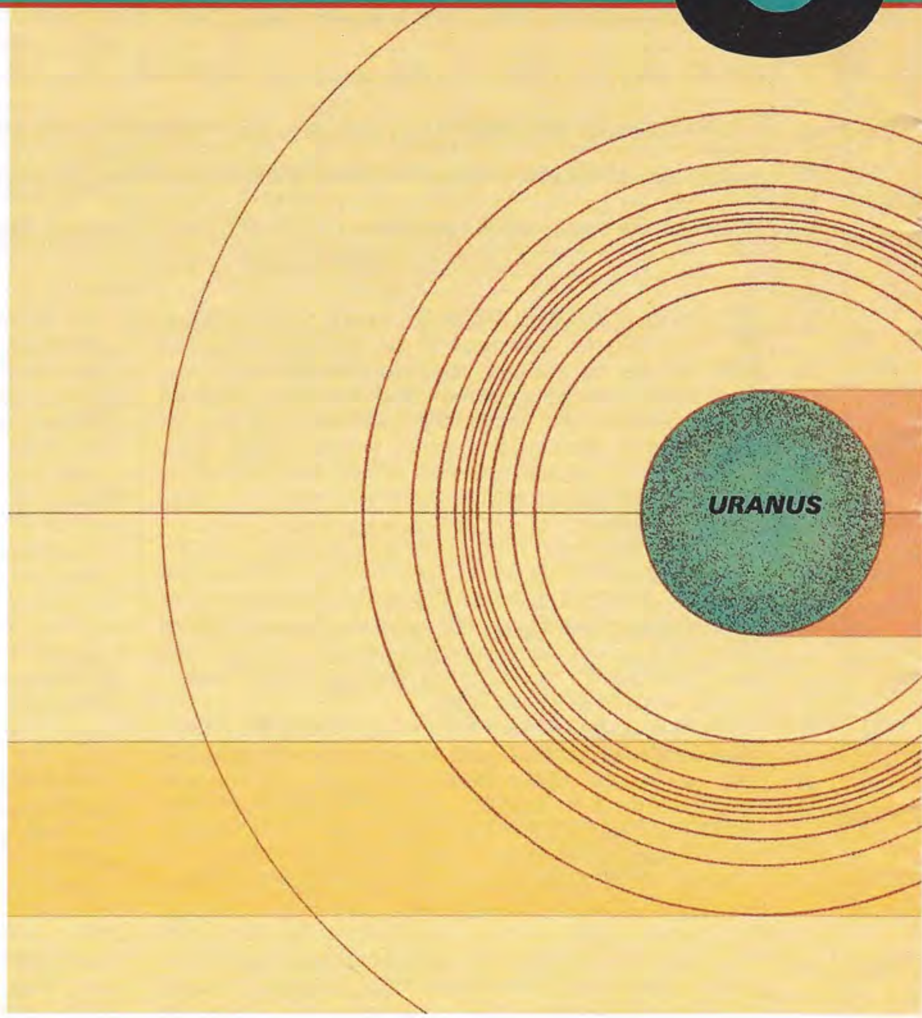
As I admired those beautiful and puzzling *Voyager* images, I wondered what William Herschel might have thought if he could see — close up — the planet he discovered over 200 years ago. Or had Gerard Kuiper lived to see the images of Miranda, would he have felt the excitement I felt in seeing the satellite he discovered nearly 40 years ago? Although I couldn't compare my contributions with those of Kuiper and Herschel, I had spent several years trying to unlock secrets of the uranian satellites, and I was ecstatic to be among the first to see them close up. I was sure that Herschel and Kuiper would have felt the same.

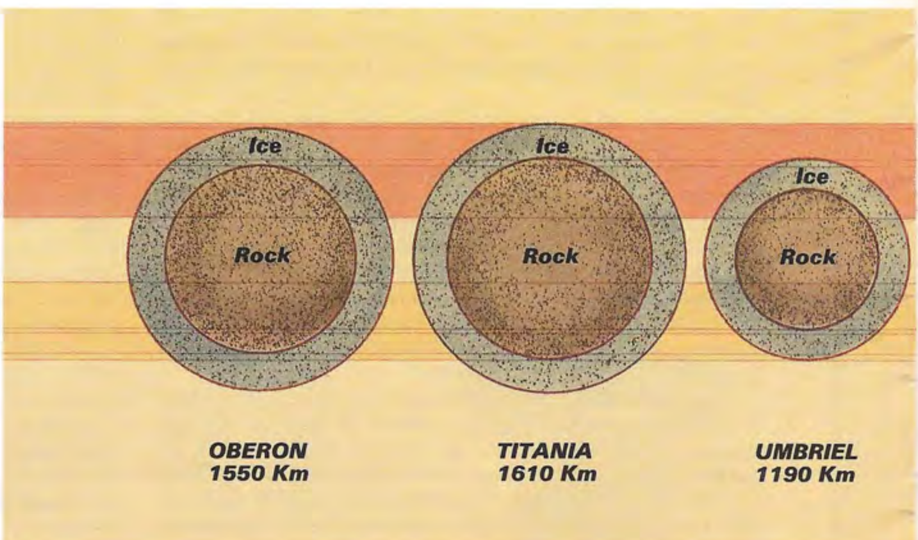
New Satellites

Among the first major discoveries made by *Voyager 2*, even before its closest approach to Uranus, were 10 previously unknown satellites. Most people on the *Voyager* project expected the spacecraft to discover new moons, but that didn't diminish the excitement when those expectations were fulfilled.

The first satellite discovered was also the largest new moon — officially dubbed 1985U1, but affectionately and unofficially called "Puck" by those who found 1985U1 just a little too generic. Puck, a character from Shakespeare's *A Midsummer Night's Dream*, seemed an appropriate nickname because all the known uranian satellites except Umbriel were named for Shakespearean characters.

1985U1 was discovered far enough

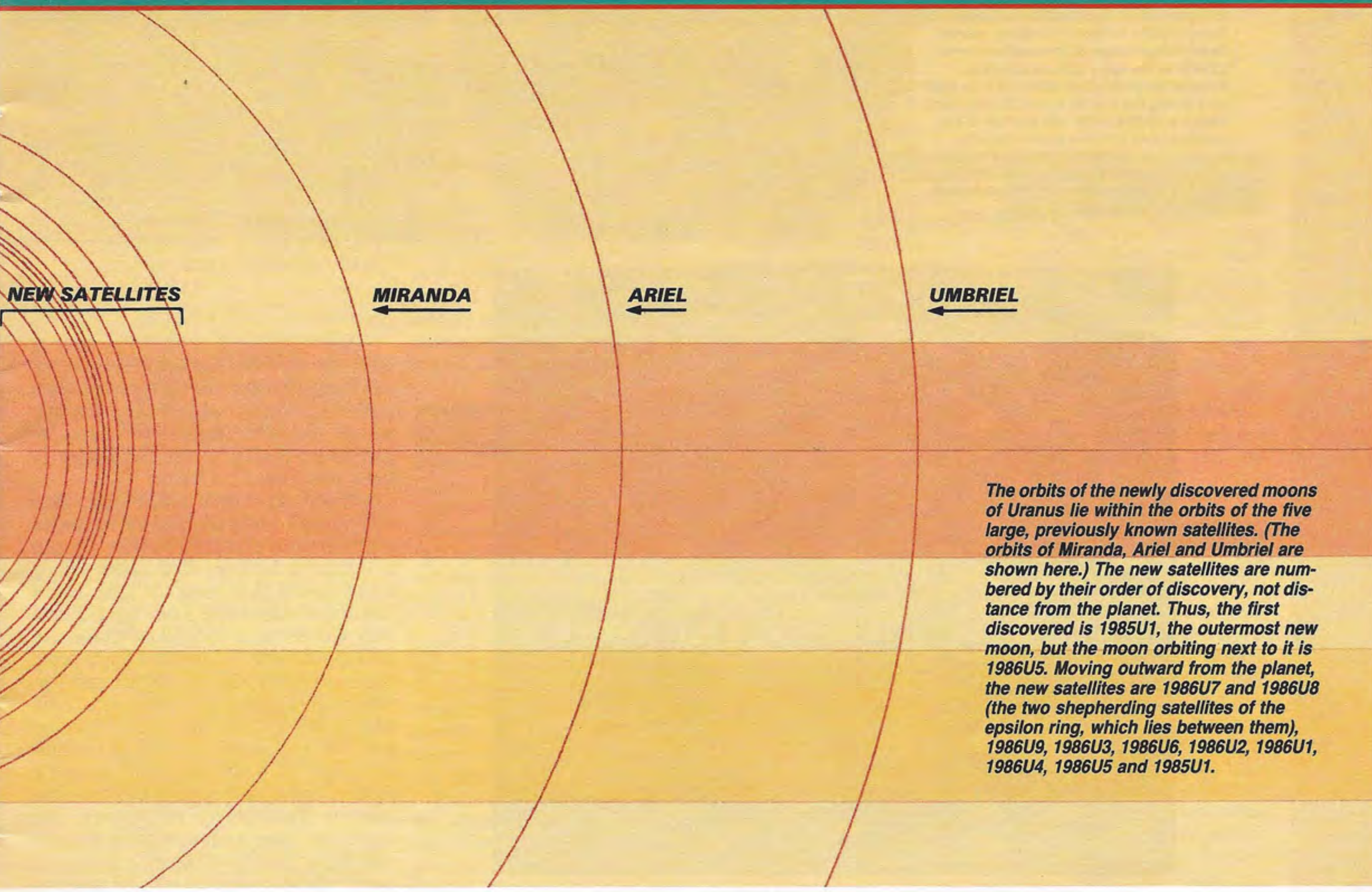




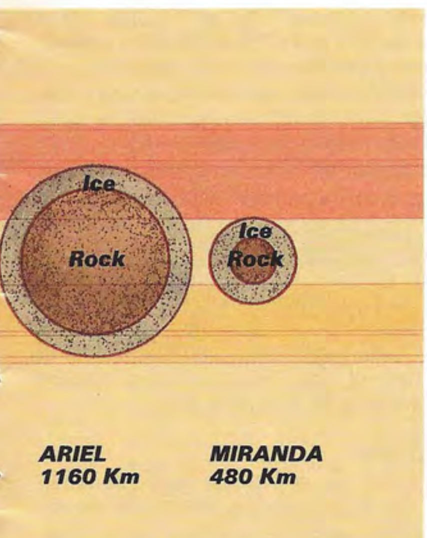
When they know the mass and diameter of a satellite, scientists can calculate its density, and so get an idea of its composition and internal structure. Here we show the relative sizes and possible internal structures of the large uranian satellites, assuming that they are made primarily of water ice (grey) and rocky material (brown) similar to that found in primitive meteorites.
Illustrations: S. A. Smith

ranian Satellites

by Robert Hamilton Brown



The orbits of the newly discovered moons of Uranus lie within the orbits of the five large, previously known satellites. (The orbits of Miranda, Ariel and Umbriel are shown here.) The new satellites are numbered by their order of discovery, not distance from the planet. Thus, the first discovered is 1985U1, the outermost new moon, but the moon orbiting next to it is 1986U5. Moving outward from the planet, the new satellites are 1986U7 and 1986U8 (the two shepherding satellites of the epsilon ring, which lies between them), 1986U9, 1986U3, 1986U6, 1986U2, 1986U1, 1986U4, 1986U5 and 1985U1.



ahead of *Voyager*'s closest approach that we were able to retarget to the new moon an image planned for Miranda. We were surprised to find that 1985U1 is roughly spherical and about 170 kilometers in diameter, making it the sixth-largest uranian satellite. Even more surprising was that 1985U1 is nearly as dark as the rings of Uranus; if you could hold it up against a white background, it would look almost as black as coal.

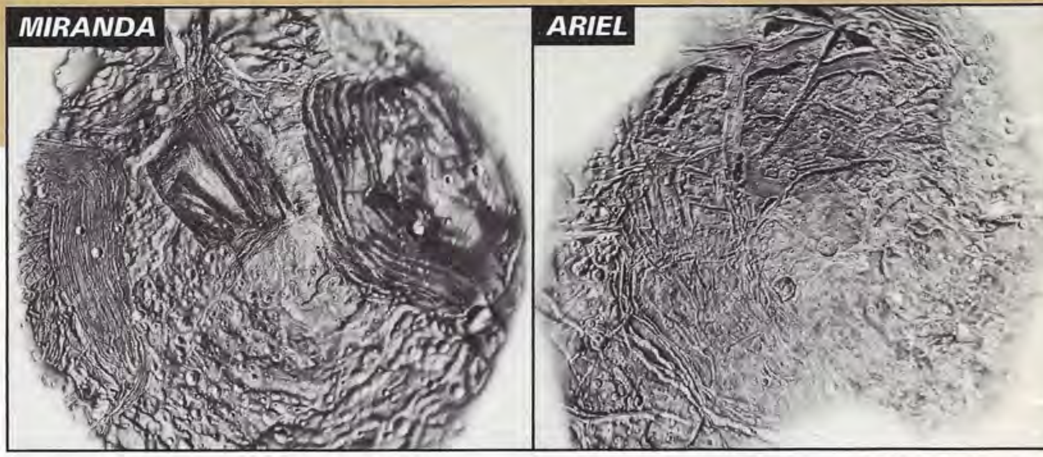
The other nine new satellites were too small for *Voyager* to take detailed images of them, but we did learn that they are all quite dark and range in size from 40 to 80 kilometers. They follow nearly circular orbits lying approximately in Uranus' equatorial plane inside Miranda's orbit. 1986U7 orbits just inside the epsilon ring, and its sister 1986U8 orbits just outside the ring, closely enough that these two satellites probably confine the ring particles in their present orbits. Without gravitational interactions with these two satellites, theoretical analyses suggest, frequent collisions between ring particles would quickly broaden and diffuse the epsilon ring.

Oberon

Exciting as the discoveries of new satellites were, *Voyager* saved the best for last. The most detailed images of the five large satellites — Oberon, Titania, Umbriel, Ariel and Miranda — were taken on the day before and on the day of closest approach. Oberon was the first to be explored close up.

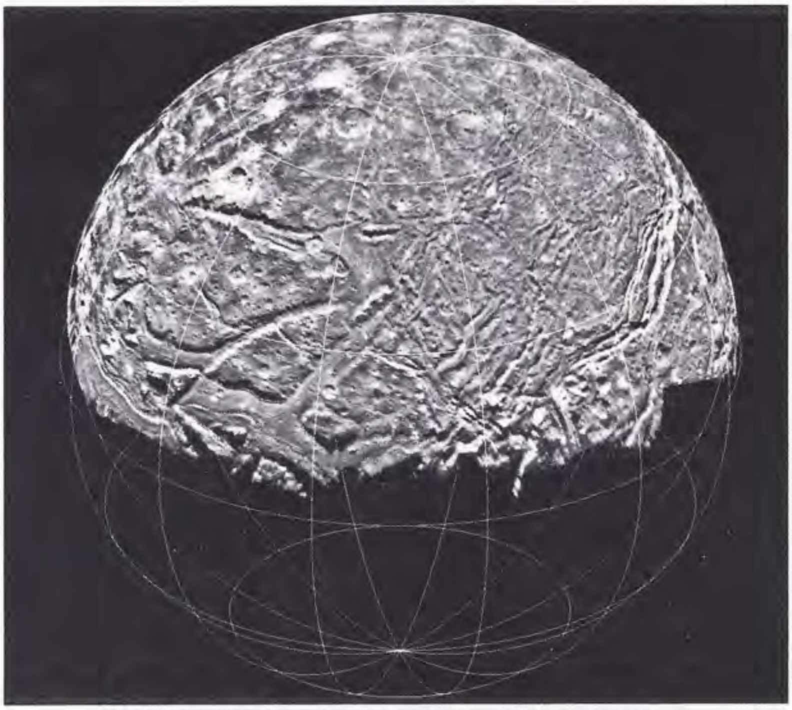
We expected to see a heavily cratered satellite, about 1,600 kilometers in diameter, that had seen little or no geologic activity since it solidified about 4.5 billion years ago. We saw a satellite 1,550 kilometers in diameter, cratered by debris that probably orbited the Sun close to Uranus early in solar system history. To our surprise, however, Oberon shows signs of early geologic activity. The images revealed a fault running across the entire southern hemisphere; we also saw large, bright-rayed craters with dark material partly covering their floors.

All this suggested that Oberon wasn't



***RIGHT:** Using imaging data from Voyager 2, cartographers at the United States Geological Survey (USGS) in Flagstaff, Arizona, created these airbrush maps of the southern hemispheres of the large uranian satellites. Because these satellites rotate once on their axes during every orbit around Uranus, they always keep the same side pointed at the planet, just as our own Moon keeps the same face toward Earth. Zero degrees longitude, at the top on these maps, indicates the center of the Uranus-facing hemisphere.*

Cartography: Pat Bridges and Jay Inge, USGS



***ABOVE:** Voyager 2 images of Ariel are here compiled by computer onto a map grid. The computer projects each frame of a set of images onto an ordinary latitude and longitude grid, as could be found on a standard globe of Earth. Image: USGS*

just a dead relic but had enjoyed an early tectonic event, with movements of its crust due to internal forces and heating, and had responded to some meteorite or comet impacts with later eruptions of dark material onto the floors of the resulting craters. Through telescopic observation we know that frozen water is plentiful on the large uranian satellites, so perhaps the "lava" on Oberon's crater floors is a mixture of dark material and frozen water. Or the water could be mixed with more volatile material such as methane, and has been altered by eons of exposure to the solar wind, whose ionizing particles can darken many materials.

Umbriel

Our experience with Oberon taught us to be suspicious of preconceptions, and Umbriel, whose early images showed a surprisingly uniform surface, compounded the lesson. Before closest approach all the large satellites except Umbriel showed patchy surfaces with bright and dark marks, but only a small, bright mark near its equator distinguished the otherwise bland disk of Umbriel.

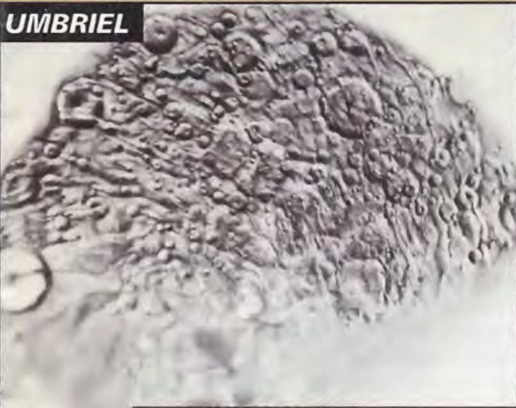
This lack of surface contrast sets Umbriel apart, and in some ways makes it the most enigmatic uranian moon. Why, we thought, has Umbriel maintained such a contrast-free surface although it's covered with large, old craters? If it formed from a uniform mixture of water ice and rock, as some theories of satellite accretion predict, then perhaps Umbriel's interior hasn't generated enough heat to melt the ice and allow the rock and dark material to differentiate and settle into its core. That would account for this darkest surface among the large satellites, and would explain why impacts haven't produced bright-rayed craters by penetrating through a thin, dark layer to fresh, clean water ice below.

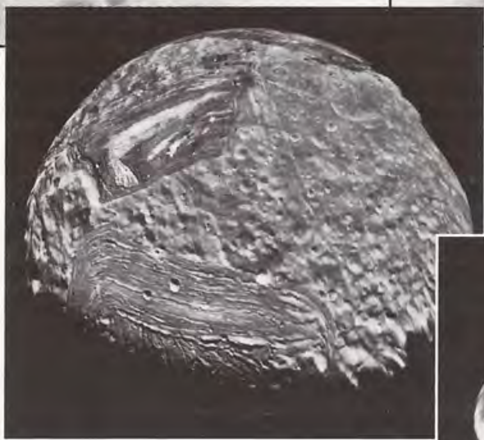
As temptingly simple as that explanation is, it doesn't easily account for the bright oval mark near Umbriel's equator, nor can it explain a medium-sized crater with a bright central peak near the oval. But if Umbriel is coated with a thin layer of dark material, it's easy to explain those two geologic features: The oval is a bright crater floor seen nearly edge on, and any dark material once covering the bright crater peak has subsided down the walls. Nevertheless, that explanation troubled us because it requires an event that could deposit a uniform layer of dark material over the entire southern hemisphere. Furthermore, the event must have occurred recently because only two or three meteorite impacts have exposed brighter underlying material. It seems unlikely that a great coating event conveniently happened, only on Umbriel, just a few million years before *Voyager* arrived.

Although there are many equally plausible hypotheses, now that we've had a few months to consider the problem, a more palatable explanation may be that Umbriel has both a thin coat of dark material and large areas of primitive, dark crust that are too thick for most meteorites to penetrate. Under that hypothesis, impacts into the dark, primitive crust would provide material to coat Umbriel, but would not form bright craters. We can then assume that the bright central peak and the oval lie in an area of clean, water-ice crust overlain by a thin layer of dark material.

Titania

If Uranus was giving us a lesson in humility, the high-resolution images of Titania, its largest satellite, continued in the tradition. Titania's geology proved different from Oberon's and Umbriel's in one important sense: Titania displays few large craters. This suggests that the large craters al-





LEFT AND BELOW: With a computer to manipulate data, scientists can view planetary bodies from varying perspectives. Here, researchers at the USGS in Flagstaff, Arizona have "painted" the Miranda mosaic onto a computerized ball. They then modified the ball to reflect the satellite's topography, with craters, valleys, scarps and other features texturing the surface. With the data in place, the ball can then be rotated, as shown here, to see the satellite from different angles. ***Images: USGS***

LEFT: Voyager 2 took a series of images of Miranda that are here compiled into a highly detailed mosaic of the moon. This is the view you would see if you looked directly down on Miranda's south pole. The "chevron" lies close to the pole. The two ovoids at left and right center are whimsically called the "circi maximi." ***Image: JPL/NASA***

most certainly present on Titania in the past have been mostly erased. In their places, smaller craters formed from debris impacts, probably from material orbiting Uranus rather than the Sun.

A reasonable scenario is that, not long after Titania's crust formed, debris left from the accretion of Uranus battered all the young satellites. Then Titania generated enough internal heat to melt and differentiate, thus resurfacing itself and destroying its original large craters. Following that, smaller debris, orbiting Uranus with lower velocities relative to the satellite, produced the small craters. Several global-scale fault systems and scarps on Titania's southern hemisphere, some with bright deposits, support the idea of early, large-scale geologic activity on this satellite.

Ariel

By now we were getting used to the idea that the uranian satellites had been much more geologically active than we had been assuming. The only exception was Ariel. Some groundbased observations of Ariel had hinted at geologic activity, and theoretical analyses of the orbital motions of Ariel, Miranda and Umbriel suggested that gravitational interactions among these satellites might have caused internal heating in Ariel.

When it returned its high-resolution, four-frame mosaic of Ariel, *Voyager* confirmed these suspicions. We were amazed by huge faults over 10 kilometers deep and hundreds of kilometers long. Ariel's fault systems are far larger and more extensive than those on Titania, suggesting that Ariel experienced large crustal adjustments early in its history.

(continued on page 18)

The Magnetosphe

Probably the most startling discovery of *Voyager 2* at Uranus was the substantial and extremely unusual magnetic field and magnetosphere. The magnetic axis is tilted 60 degrees from the planet's rotation axis, and the magnetic dipole center is displaced almost 7,700 kilometers from the center of the planet (see box, page 10). At Earth, the dipole is tilted only 11.7 degrees and the offset is less than 500 kilometers. Earth's magnetic field intensity varies over its surface between 24,000 and 69,000 gammas, while Uranus' field varies between 10,000 and 110,000 gammas. (A long wire carrying one milliamp of current generates a magnetic field of 20 gammas one centimeter from the wire.) Since most of our knowledge of planetary magnetospheres is based on Earth's, the uranian magnetosphere presents us with an intriguing puzzle.

The strangeness of the magnetic field and magnetosphere adds to the well-known mystery of Uranus' rotation axis, which points eight degrees below its orbital plane. Uranus spins like a top lying on its side, with its spin axis now pointed almost directly at the Sun. Confined around the planet and partly blown back by the solar wind, the magnetosphere — the region of the planet's magnetic influence — twists like a corkscrew as it rotates. This is a world very different from Earth.

Before the *Voyager 2* encounter, we had no firm evidence for a magnetic field at Uranus, and indeed, no consensus among theorists as to whether we should expect one. Ground-based radio astronomers unsuccessfully tried to detect radio signals from the planet, which would have revealed the presence of a magnetosphere. En route to their earlier encounters with Jupiter and Saturn, both *Voyagers 1* and *2* had detected radio emissions from those planets. Based on comparisons with Earth, Michael Desch and Michael Kaiser, radio astronomers at NASA's Goddard Spaceflight Center, had confidently predicted early in 1984 that *Voyager 2* would detect signals from Uranus sometime between December 1984 and May 1985, while the spacecraft was still millions of kilometers away.

But in January 1986, as *Voyager 2* neared encounter, Uranus remained radio quiet. People began wondering if perhaps this strangely tilted planet had no magnetic field. Then, five days before closest approach, *Voyager 2* finally detected radio signals from the planet. During the next 35 days we observed a rich spectrum of radio signals, mainly from the nightside magnetosphere. At the same time, the spacecraft's instruments directly measured Uranus' magnetic field and its trapped radiation belts.

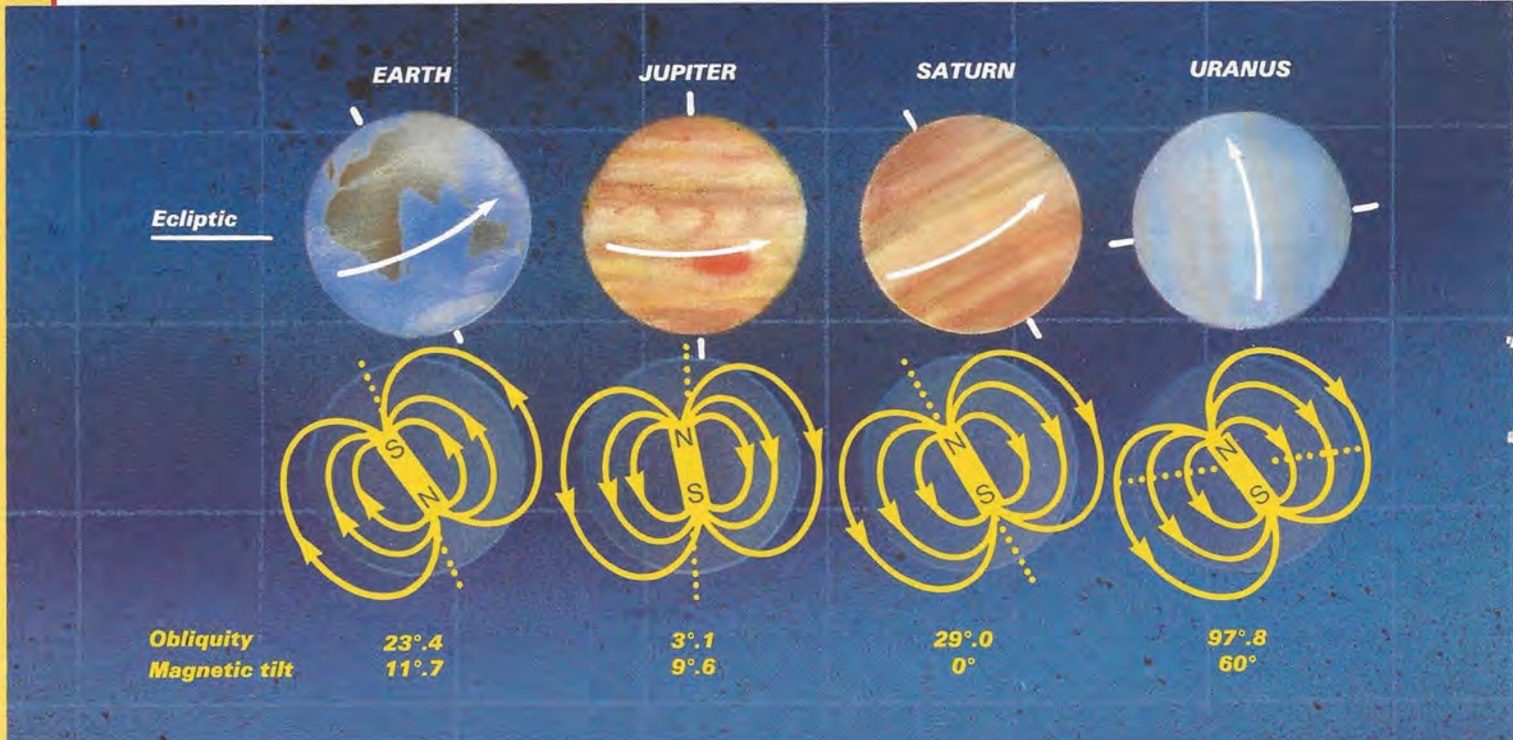
Planetary Dynamos

Planetary magnetic fields are believed to be generated by a "dynamo" inside the planet. The motion of an electrically conducting fluid (for example, Earth's dense, molten core) amplifies a primeval, or "seed," magnetic field, which then leaks out to fill the space around the planet. By studying irregularities in the magnetic field, scientists can infer properties of the interior of a planet, such as the westward drift or differential rotation of Earth's electrically conducting core — where the dynamo is active — relative to its outer layer, the mantle.

The only plausible explanation for the magnetic field at Uranus is that it is generated by an active dynamo. In the case of Uranus, whose average density is only 30 percent greater than water, we are uncertain what energy source lies in the planet's interior. While it may be gravitational settling of heavier materials, it may also be heat from radioactive decay. The existence of this planetary magnetic field constrains scientists' models that attempt to represent the internal structure of Uranus.

Aurora

One feature of Earth's magnetosphere, known to humans for centuries, is the aurora. These mysterious lights appear



re of Uranus

by Norman F. Ness

sporadically in the Arctic and Antarctic night sky. They form as radiation-belt particles rain into Earth's atmosphere. The charged particles excite neutral atmospheric atoms, and energy is given off in both visible and ultraviolet wavelengths.

With this phenomenon in mind, more than five years ago scientists turned the telescope of the International Ultraviolet Explorer (IUE) Earth satellite to Uranus. Since these were not high-priority studies, the observing time was limited. Nonetheless, tantalizing ultraviolet signals were reported, suggesting auroral activity. Extrapolating further, scientists indirectly deduced that there might be a magnetic field and magnetosphere with trapped radiation belts.

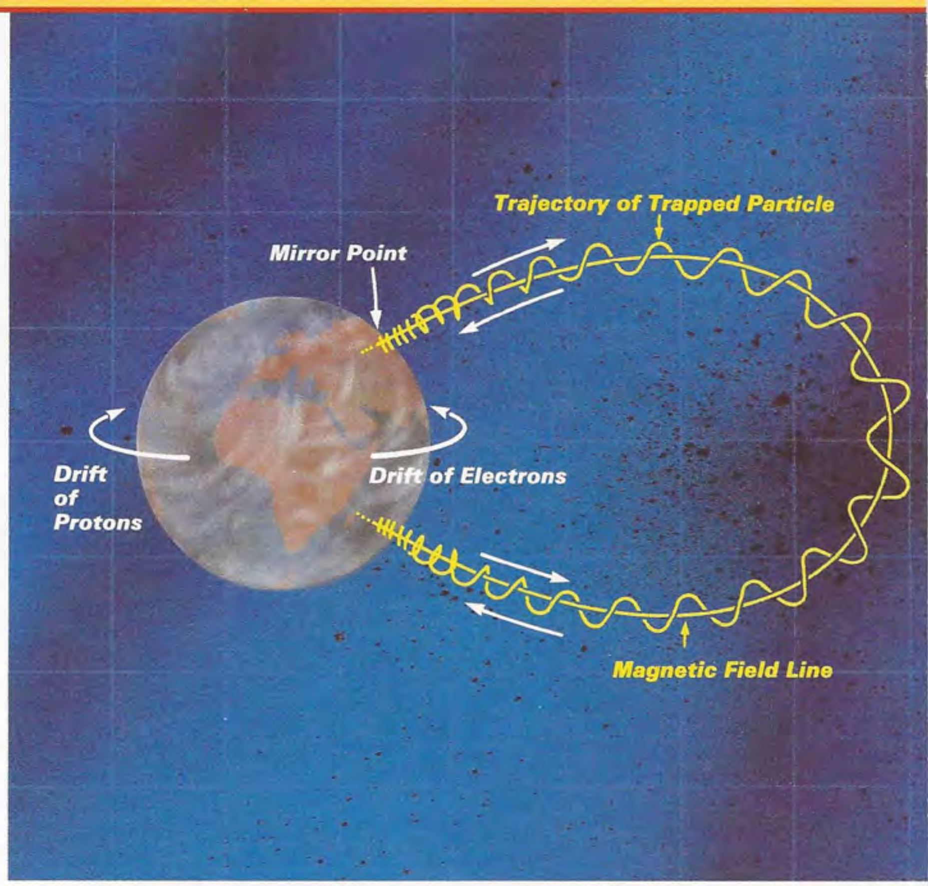
The *Voyager 2* ultraviolet experiment found some evidence for an aurora, but only on Uranus' nightside. In planning the observations, scientists had been guided by their experience of Earth, Jupiter and Saturn, where auroras are associated with the magnetic polar regions of the planets. Since at these planets the fields are tilted only slightly or not at all (11.7, 9.6 and 0 degrees, respectively), the auroras are seen close to the rotation poles.

At Uranus most scan sequences for the ultraviolet auroral studies had been planned to look in what turned out to be the wrong place! The magnetic poles and auroral zones are much closer to the equator than at the other planets. In the presently sunlit, northern hemisphere, the magnetic pole (positive) is at a latitude of +15.2 degrees, while the southern (negative) pole is at −44.2 degrees.

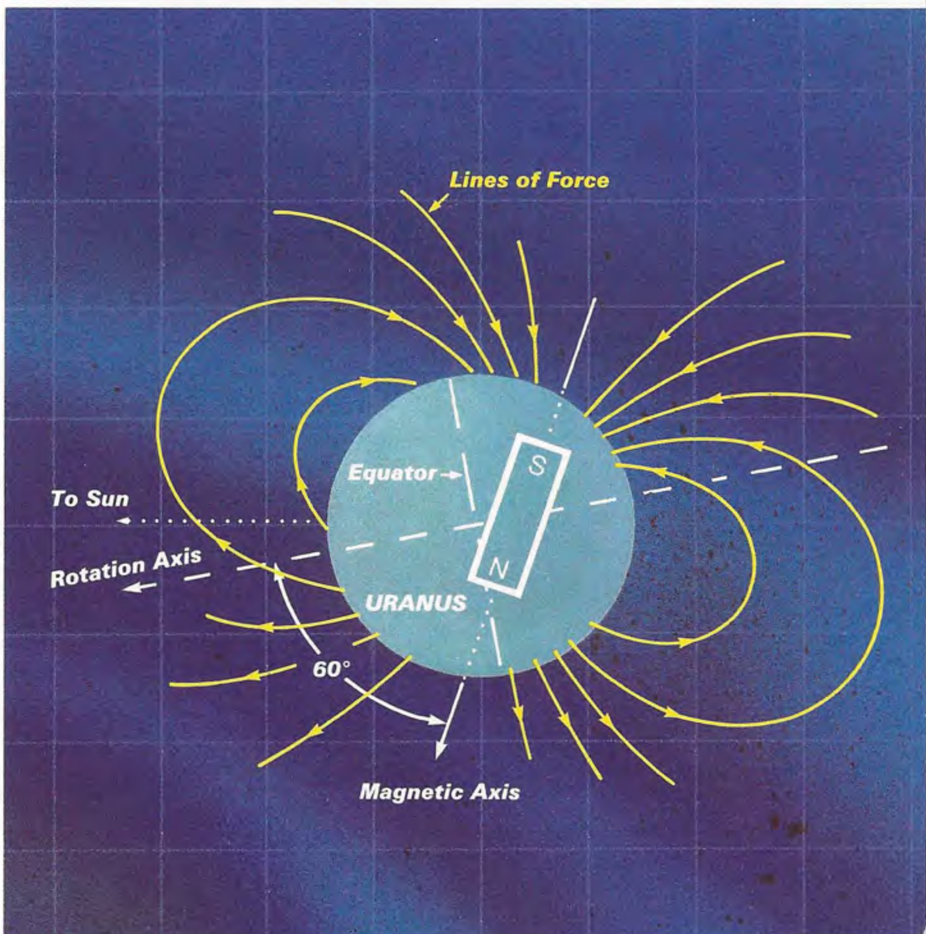
A mysterious ultraviolet signal was observed, but only on the dayside. This almost uniform emission of ultraviolet light has been called the "electroglow." This refers to a process of both molecular and atomic hydrogen emission, observed at Jupiter and Saturn and thought to be caused by excitation by low-energy electrons. There is now some doubt that the earlier IUE results represent detection

(continued on next page)

LEFT: The uranian magnetic field is the strangest of all the planets yet investigated. At Earth, Jupiter and Saturn, the rotation axis of the magnetic field is more or less aligned with the planet's rotation axis. At Uranus, it is offset by 60 degrees. The planet's rotation axis is also unusual: It's tilted 97.8 degrees from the ecliptic (the imaginary plane defined by the orbits of the planets around the Sun). In this chart, obliquity is the measure of the planet's rotational tilt; magnetic tilt measures the tilt of the magnetic field from the rotational axis.



UPPER RIGHT: Belts of charged particles surround the best-studied planet, Earth, just as they do Uranus. (See box, next page.) The particles, spiraling around magnetic lines of force, bounce back and forth within these radiation belts, reversing direction at "mirror points," where the lines of force converge. Negatively charged electrons drift eastward, while positively charged protons move westward.



RIGHT: Using data returned by Voyager 2, scientists sketched out the major elements of the uranian magnetic field. The planet rotates on its side, with its south pole now pointing almost directly at the Sun. The magnetic axis is tilted 60 degrees away from the rotational axis — the largest magnetic tilt yet measured in our solar system. The magnetic axis is also offset from the center of the planet, indicating that the internal dynamo producing the magnetic field may not be spherical. *Illustrations: S. A. Smith* of auroral signals. They may have been simply observations of the electroglow, since only the dayside magnetic polar regions were observable by IUE.

Rotation Period

One of the fundamental parameters describing a planet is its rotation rate, or the length of one day. Attempts to determine Uranus' rotation rate by Earth-based telescopic studies of its atmosphere led to a range of values between 15 and 17 hours. By carefully studying the *Voyager* data on magnetic fields and radio signals, Michael Desch, J.E.P. Connerney and Michael Kaiser at the NASA Goddard Spaceflight Center have determined a rotation period of 17.24 hours. This value is important to interpreting the internal structure of the planet, and more important to the analysis and interpretation of the atmospheric cloud motions.

Magnetospheres — The Big Picture

The earliest scientific discovery of the space age was that radiation belts surround Earth. In 1958, using data from early Explorer *spacecraft, James Van Allen and his colleagues at the University of Iowa discovered that belts of charged particles — negatively charged electrons and positively charged protons — were trapped around Earth, and the force holding them there was not gravity, but Earth's magnetic field. The fluid interior of the rotating planet acts as a dynamo, producing electric currents. These currents, in turn, produce the magnetic field which is described by measures of its magnitude and direction.*

Thomas Gold of Cornell University introduced the word "magnetosphere" into the scientific lexicon to describe the sphere of influence of a planet's magnetic field. Magnetospheres are the largest "objects" in the solar system: The Sun's sphere of influence is believed to extend beyond Pluto while Jupiter's magnetosphere stretches for millions of kilometers.

We now know that five planets in our solar system (Mercury, Earth, Jupiter, Saturn and Uranus) possess magnetospheres — the regions around each planet where their own magnetic fields dominate the behavior of charged particles. (Venus has no intrinsic magnetic field, and we're not sure about Mars.) Outside these magnetospheres, interplanetary space is dominated by the Sun's magnetic field and the solar wind, a stream of gaseous material blowing out from the Sun.

Many other objects in the universe, such as stars and pulsars, also rotate rapidly and generate intrinsic magnetic fields. Our understanding of these remote objects has been gained by ground-based astronomers detecting gamma rays, x-rays, electromagnetic signals, radio waves and light from them. Variations in these signals allow scientists to deduce properties such as rotation period, tilt between magnetic and rotational axes, and intensity of the magnetic field.

Magnetic forces act on charged particles in what may, at first, seem to be a very strange way. If the charged particle is at rest, relative to the magnetic field, then it feels no effect. However, if the charged particle is in motion, there is a force on it perpendicular to both the magnetic field direction and the motion.

Earth's magnetic field can be simply approximated as a magnetic dipole — similar to a bar magnet with one end positive, the other negative. Earth's magnetic forces cause the charged particles in the radiation belts to travel on complex trajectories. Each particle follows a helical, corkscrew-like path around a magnetic line of force — a mathematical construction showing the direction of the magnetic field at each point in space. Because Earth's magnetic field increases in intensity from equator to poles, the charged particles bounce back and forth between the polar regions. The particles' trajectories drift eastward for electrons and westward for protons. This bouncing and drift motion spreads the radiation belts into a shell-like configuration somewhat like the concentric layers of an onion.

Energetic particles are similarly trapped in some other planets' magnetospheres, as well as in those of stars and pulsars. At Jupiter, with sulfurous volcanic emissions from its moon Io, large amounts of sulfur and oxygen ions fill its radiation belts.

The electrons and their interactions with ions and protons in the magnetospheres and atmospheres generate electromagnetic waves. By carefully studying the full spectrum of signals from these objects, we can learn much about them and their environments without actually going there. For example, Jupiter's giant magnetic field was discovered over 15 years before a spacecraft arrived there, but the radio signals from it were not easy to interpret because Earth's radiation belts had not yet been discovered.

Now, with knowledge combining the results of theory, spacecraft data, and ground-based observations, we are beginning to understand this rich and fascinating magnetic phenomenon. But we still experience wonderful surprises — as in the discovery of the strange magnetosphere of Uranus. □

Magnetic Tail

Like the magnetospheres of other planets, Uranus' magnetosphere is deformed as the solar wind flows around it, compressing it on the dayside and extending it on the nightside. About 600,000 kilometers from the planet, *Voyager 2* crossed a detached "bow shock," formed when the solar wind meets the magnetosphere. The dayside magnetosphere boundary was then detected about 470,000 kilometers from Uranus. The magnetic field blown back on the nightside forms a huge magnetic tail similar in structure to Earth's.

These magnetic tails, like cometary ion tails, always point away from the Sun, streaming back in the solar wind like a wind sock at an airport. They contain magnetic lines of force bunched into two separate and oppositely directed bundles connected directly to the two magnetic polar regions. Because Uranus' rotation axis today points almost at the Sun, and because there is a large angle between the magnetic and rotation axes, the magnetic tail rotates 360 degrees once each uranian day around the extended Sun-planet line. As it rotates, the magnetic tail twists into a slight corkscrew shape, which Ken Behannon of NASA Goddard has found to be five degrees. (At Earth, the tail wobbles only a little.)

Moons and the Magnetosphere

Within the uranian magnetosphere lie radiation belts of charged particles, similar to Earth's Van Allen Belts. The great tilt between magnetic and rotation axes leads to much more complicated radiation belts than those of other planets. At Uranus, the five major moons — Miranda, Ariel, Umbriel, Titania and Oberon — orbit within the belts. Earth's Moon orbits outside our magnetic field, and so is not much affected by it. But the uranian moons sweep out large sections within the belts, absorbing trapped energetic particles. Their surfaces, covered mainly with methane ice, darken in the process. These moons are among the darkest in our solar system, due in large part to this radiation damage.

Significance

What is the significance, for the interior of Uranus, of the large tilt and offset of its magnetic axis? We may be observing a reversal of the polarity of the magnetic field, as has happened often in Earth's past. The large offset clearly reflects that the internal dynamo is far from spherically symmetrical. Is only the planet's dynamo, or is its internal structure also not centered? Could a catastrophic collision while the planet was forming, perhaps dramatically tilting its rotation axis, also be responsible for the strange magnetic field? Continued study of these *Voyager 2* data should provide clues.

Voyager 2 made important discoveries about Uranus and its magnetosphere. But as is often the case with discovery, the results present many new mysteries to be solved. Steve Curtis, my colleague at NASA Goddard, and I expect that Neptune will have a significant magnetic field and a fully developed magnetosphere in which the moon Triton orbits. We will know for sure on encounter day, August 25, 1989, but maybe before then the detection of radio or ultraviolet signals from the planet will give us preliminary indications. Stay tuned in! Dynamo and magnetosphere theorists have much to work on in the meantime.

Norman Ness is a space scientist at NASA Goddard Space Flight Center. He has been principal investigator for magnetic field studies on 18 spacecraft missions including Voyagers 1 *and* 2.

Voyager 2 and the Uranian Rings

by Carolyn C. Porco

In the 4th century B.C. Aristotle asserted that the circle, and concomitantly the sphere, were the most perfect forms, and consequently no other curve of heavenly motion or shape of celestial body was to be given serious consideration. According to the early Greeks, the universe was a neatly arranged sphere-within-a-sphere carrying the planets, the Sun and the stars around Earth. In later concepts, the spheres of the planets and the Sun moved on epicycles in circular motion around Earth. Even Nicolas Copernicus, who boldly placed the Sun at the center of the planetary system, was so firmly attached to the idea of perfectly circular motion that he, too, used circular epicycles to represent what Johann Kepler later showed was simple elliptical motion.

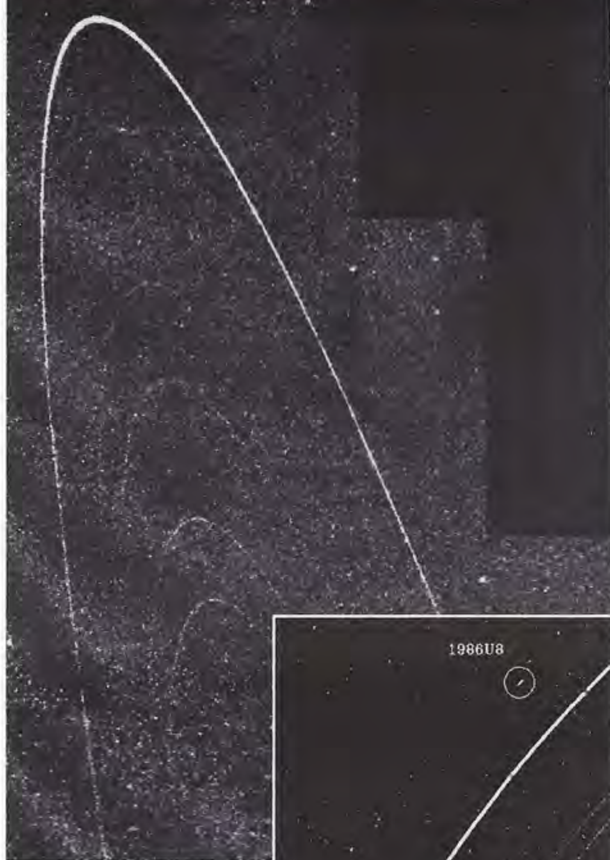
The discovery of planetary rings was part of the 17th century revolution in astronomical thought. In 1610, Galileo Galilei discovered the rings of Saturn. (Sadly, he never knew exactly what they were; that explanation was left to Christiaan Huygens several years later.) The drama and revolution of Galileo's discovery lay in its splendid demonstration that not all heavenly bodies are spheres. He had accidentally found a second major class of object, the disk, in the heavens alongside the sphere. We now know that the universe is populated with many examples of disks — giant spiral galaxies, accretion disks around stars — and that, under the proper circumstances, spheres may evolve into disks.

For 370 years, Saturn's rings remained the solar system's only known example of the celestial disk. Then, in 1977, a team of scientists, studying the atmosphere of Uranus by observing the planet's occultation of a star, discovered — also accidentally — that Uranus, too, is encircled by rings. Since that discovery, we've learned much from ground-based observations of that distant disk system.

These observations revealed a system of nine narrow rings, ranging in width from a few kilometers to about 100 kilometers, and separated from one another, in some cases, by thousands of kilometers of empty space. This is very unlike the continuous distribution of matter in the saturnian rings. Most uranian rings are eccentric, inclined to Uranus' equatorial plane, and precessing (wobbling) as would the orbit of a single body.

The discovery of the uranian rings sparked a flurry of theoretical activity. No ring in orbit about a planet can remain narrow; particle collisions, solar radiation pressure, and atmospheric and plasma drag forces would disperse a narrow ring and cause it to spread. The most convincing hypothesis to explain the narrow uranian rings suggested that small satellites, one on either side of each ring, could gravitationally confine a ring, thus "shepherding" the material between them. The uranian rings must thus be attended by an entourage of tiny shepherding satellites. A set of eccentric narrow rings very similar to the uranian rings is embedded in the broad rings of Saturn. In a sense, the uranian rings are a distillation of the vast saturnian system. To know one is to know the other.

Being so distant and so narrow, the uranian rings are unresolvable in images taken from Earth; most of our knowledge comes from stellar occultations. What sparse imaging observations were made, however, indicated that the ring system was very dark, reflecting only about two percent of the visible sunlight falling on it. In contrast, Saturn's rings reflect about 60 percent of the light. The particles in the uranian rings, it was guessed, are made of water ice like Saturn's, but are contaminated by carbon-bearing molecules such as methane (CH_4). Methane could more easily exist in the -200 degree Celsius temperature of the uranian environment than in the warmer surroundings of Saturn. Bombardment by charged particles in a strong uranian magnetosphere, if there



ABOVE: As Voyager 2 neared its ring plane crossing, it took three images of the rings that have been constructed into a mosaic. The newly discovered ring, 1986U1R, is faintly visible between the brightest and outermost ring, epsilon, and delta, the next adjacent bright ring.

INSET: Scientists suspected that the uranian rings would be confined by shepherding satellites, whose gravity confines the ring particles to a narrow path. Voyager 2 partly confirmed those suspicions when it discovered 1986U7 and 1986U8 orbiting on either side of the epsilon ring. *Images: JPL/NASA*

LEFT: As it moved behind the rings and into the shadow of Uranus, Voyager 2 took this unusual image of the rings. Here, backlit by the Sun, broad bands of smoke-sized particles appear among the narrow known rings. In this 96-second exposure, the uranian rings appear to resemble the much broader and denser rings of Saturn.

were one, could release the carbon from the methane and thus darken the rings.

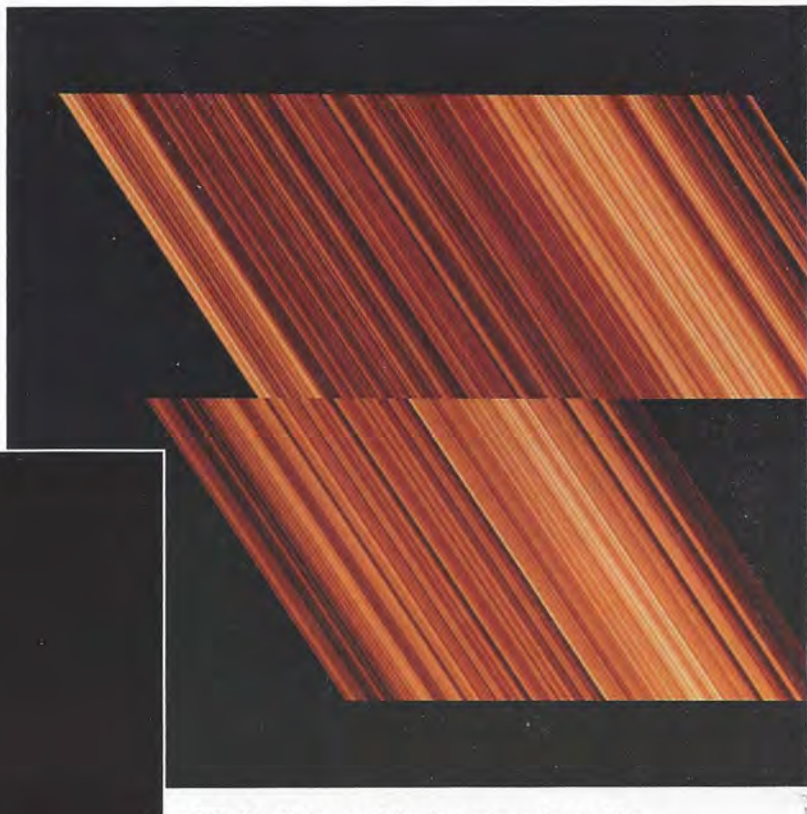
The uranian rings are much less massive than Saturn's. The entire system could be compressed into an icy body only 15 kilometers in radius; the mass of Saturn's rings is equivalent to a 150-kilometer body. If these systems formed from the destruction of satellites, then they were satellites of very different size. However, both systems are very flat, made of myriads of particles, each in its own orbit, but continually perturbing and colliding with its neighbors. And both systems lie within their Roche limit, that imaginary boundary around a planet within which particles cannot gravitationally coalesce to form a satellite because of the disruptive effect of planetary tidal forces. So perhaps these disks did not arise from satellites but are the flattened remnants of the protoplanetary nebulae from which the planetary systems formed.

As *Voyager 2* sped toward its destination, questions like this weighed on the minds of those fascinated with planetary rings. Special imaging sequences were designed to search the entire ring system for shepherding satellites. Would we find them? If none were visible to the cameras, would we see structure within the rings that would betray the satellites' existence? Would all the rings be equally dark? Would they all have the same color? Rings of differing reflectance and color would be strong evidence for differing origins, perhaps from distinct satellites. Would the distribution of particle sizes be characteristic of a collisionally evolved system? And finally, what new and unexpected phenomena would we discover?

Although conducted from 3 billion kilometers away, *Voyager 2*'s encounter with Uranus was an engineering marvel and a remarkable scientific success. The *Voyager* team met the challenges of the immense distance, low data return rates, faint solar illumination and inherent ring darkness, and ring scientists reveled in an unforgettable view of this ethereal system. The images returned reveal the rings to be everything we had imagined: narrow, dark, almost ribbon-like.

In a high-resolution image taken only one day from encounter, we discovered a narrow and very faint ring between the outermost delta and epsilon rings. This ring, temporarily named 1986U1R, hadn't been detected in ground-based observations because of its narrowness and extremely low particle density.

While *Voyager 2* was still about 30 days from closest approach, it discovered a satellite orbiting midway between the rings and the innermost previously known satellite, Miranda. By the end of encounter we had found 10 new satellites, ranging in diameter from 40 to 170 kilometers. Two of these tiny satellites, 1986U7 and 1986U8, straddle the epsilon ring and act



***LEFT:* Not all images of the rings are products of the cameras on *Voyager 2*. The spacecraft's photopolarimeter (PPS) can lock onto a star and measure how the intensity of starlight changes as the rings occult the star, as they pass between it and the instrument. The measurements can be converted into images revealing the structure and amount of material within the rings. Red areas represent regions of sparse material, yellow areas regions of dense material. Four slices (left), through the epsilon ring, show how the ring appears to expand and contract like an accordion. The two top left slices were constructed from the occultation of the star Beta Perseii, the bottom two from Sigma Sagittarii. A close-up of the Sigma Sagittarii image is shown above.**
Images: JPL/NASA

***ABOVE:* Scientists were able to construct the photopolarimeter data into images of the five most opaque uranian rings. White indicates areas dense in particles, blue indicates areas of sparser particles.**
Image courtesy Larry Esposito, University of Colorado

as shepherding satellites just as we had expected. At least for one ring, we found the elusive shepherds. Any other shepherding satellites must have diameters smaller than 20 kilometers, or *Voyager 2* would have detected them.

Images taken as *Voyager 2* approached the uranian system show that the rings are *very* dark — individual particles reflect only about five percent of the light falling on them. And the most easily measurable ring, epsilon, is visually monochromatic. We are uncertain whether the other rings are equally colorless. This lack of color in the rings, as well as in the satellites, compared to their distinctly reddish jovian and saturnian counterparts, is an issue that *Voyager* has brought to the fore. Because the colors of materials are a clue to their compositions and histories, this greatly interests scientists eager to understand the chemical evolution of our solar system.

As *Voyager 2* shot through the ring plane, its cameras took a dramatic series of images. All nine previously known rings, and tenth ring 1986U1R, were easily seen in this ring plane crossing mosaic. The innermost frame of the series, designed to scour the region inside the known rings for new material, revealed a broad, diffuse and faint ring never seen from Earth. Known as 1986U2R, this ring is about 2,500 kilometers wide, and is unlike any other ring in the system. Might it be a temporary repository of small particles being swept toward Uranus from the other rings? We cannot say for sure. This question will receive a lot of attention as scientists puzzle over the origin and destiny of 1986UR2.

Shortly after its ring plane crossing, *Voyager 2* made its way behind the rings into the shadow of Uranus. Here, from a position advantageous for detecting submicron (smoke-sized) particles, the wide-angle camera was turned toward the Sun and targeted to the rings. We then took the most startling ring image of the whole encounter (see page 11). It clearly reveals that the entire ring system is almost completely awash in very tiny particles.

The resemblance of this image to images of Saturn's rings is striking, but the story told by this image is even more exciting. In any planetary environment, we expect small particles to live only a short time. Many of the same forces that disperse narrow rings act on small particles even more quickly, sending them spiraling into the planet or expelling them from the system. Thus, the fine material we see in this image and its distribution indicate active processes of dust creation and removal from very localized sources, such as collisions in the rings or meteorite impacts.

But despite ubiquitous tiny particles in the uranian ring system, the actual amount of dust is amazingly small: only about 0.1 to 0.01 percent relative to larger particles, compared to a dust content of several percent in the thickest parts of Saturn's rings, and about 50 percent in Jupiter's ring. This strange finding was confirmed by other experiments aboard *Voyager 2*. The radio science occultation experiment provided the first measurements of the rings at radio wavelengths. It found the nine main rings to be devoid of particles smaller than a centimeter. The photopolarimeter instrument observed two stellar occultations — analogous to the stellar occultations observed from Earth — and the results were similar: little or no dust. The particle size distribution in the uranian rings is not what we might expect for a system that has reached collisional equilibrium — a system where particles are accreting as fast as they are destroying each other. Why?

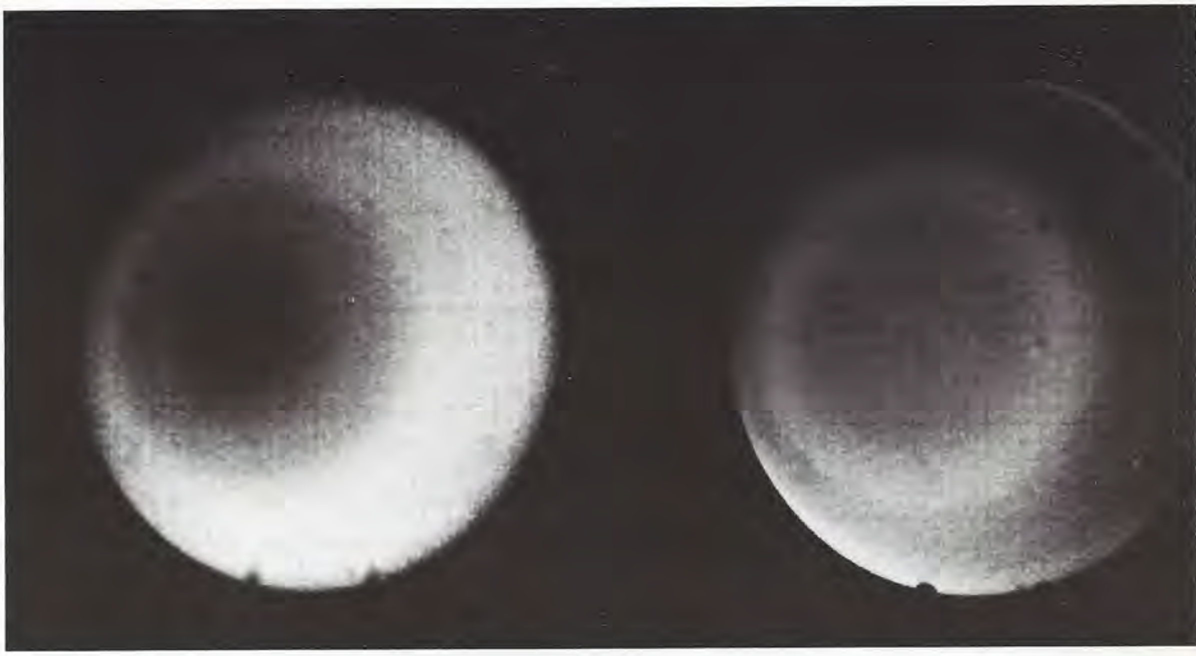
As part of its ring-plane-crossing sequence, Voyager 2's wide-angle camera examined the area inside the innermost known ring. There it found a broad, faint ring unlike any other in the uranian system. In this highly-processed image, this new ring appears as the faint bright arc in the right half of the picture. ***Image: JPL/NASA***

The answer was provided by yet another experiment, the ultraviolet spectrometer, which showed the predominately hydrogen atmosphere of Uranus to be extremely bloated. As far out as the epsilon ring, the density of atomic hydrogen is large enough to sweep dust particles into the planet on short order — much less time than the age of the solar system. Any fine material created in the uranian rings, either by collisions between ring particles or by micrometeorite impact on larger bodies, is quickly removed. Our stunning wide-angle image is but a single frame in a motion picture documenting the erosion of the entire uranian ring system.

Voyager 2's reconnaissance of the uranian environment is over. The spacecraft is now making its way toward its last planetary rendezvous, Neptune, a planet promising another ring system, perhaps more intriguing than any seen so far. There will not be another Uranus encounter for a long, long time. We are privileged, though, for the *Voyager 2* encounter with the uranian rings has left us with mysteries to ponder and an indelible impression of what scientific inquiry is about.

Carolyn Porco is a planetary scientist at the University of Arizona's Lunar and Planetary Laboratory. She is a member of the Voyager *Imaging Team and her specialty is planetary rings.*

Voyager 2 Investigates the



by Garry Hunt

Brightly banded Jupiter, subtly striped Saturn, these are what giant gaseous planets are supposed to look like. Zonal winds form bands of clouds, blowing east-west around the axis of rotation and giving these planets their distinctive striped look. Uranus is the third largest giant planet, with a soft blue-green color. Many scientists expected it to display the same sort of cloud bands, marked by occasional storms, as do Jupiter and Saturn. But as **Voyager 2** ***neared Uranus, images of the planet remained a hazy, featureless blue. Indeed, some atmospheric scientists began to wonder if*** **Voyager** ***would give them anything visual to study (see the March/April 1986*** **Planetary Report.*)***

But the **Voyager** ***images of what seems a featureless planet can be computer-enhanced to bring out faint details. And data from the spacecraft's other instruments, when combined with visual images, have allowed scientists to piece together a picture of Uranus' atmosphere.***
—EDITOR

Composition

The atmospheres of the giant outer planets are hydrogen-rich envelopes, very different from the oxidizing atmospheres of the terrestrial planets. They also contain large amounts of helium, the second most abundant element in the universe. *Voyager 2* found Uranus to have about 15 percent helium, comparable to the amount we believe to have been present in the parent solar nebula from which the planets formed.

Methane (CH_4), though it makes up only a few percent of the atmosphere, gives Uranus its characteristic blue-green color by absorbing red light. Ground-based observers had also found acetylene (C_2H_2), a more complex hydrocarbon formed as the Sun's ultraviolet light breaks down methane molecules. The *Voyager* spacecraft detected traces of deuterium, in the form of HD and CH_3D, and ammonia (NH_3).

Structure

Although the gaseous planets are similar in composition, there are important differences in their atmospheric structures. Their temperature profiles are determined mainly by heat balance, which is influenced by solar and internal heating, and by convection within the atmosphere. Uranus has a negligibly small internal heat source, with an effective temperature of −216 degrees Celsius.

Uranus is tilted 98 degrees to the plane of the ecliptic (the plane described by the planets' orbits about the Sun), and this causes interesting seasonal effects over the 84 years it takes Uranus to orbit the Sun. The other planets rotate around axes more or less perpendicular to the ecliptic, but Uranus' axis of rotation lies almost in the plane of its orbit. Consequently, each pole spends 42 years in sunlight.

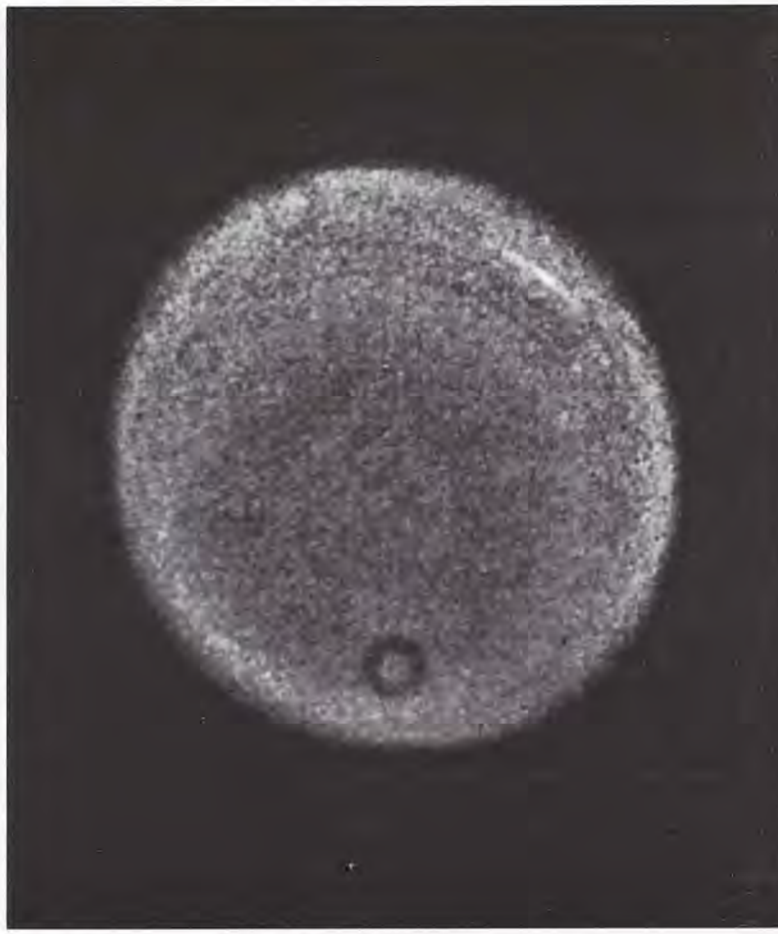
Voyager 2 detected some effects of this seasonal lag in the atmospheric temperatures. In the lower stratosphere, the dark pole was two to three degrees Celsius warmer than the illuminated pole. We estimate that the temperature varies only about five degrees from season to season. The atmosphere in the winter hemisphere is very slowly cooling. There are some small variations in temperature near the cloud tops, but in general the atmosphere is surprisingly uniform.

Clouds, Hazes and Motions

Uranus is so far from Earth that clouds cannot easily be observed from here. We thought the atmosphere was cold and clear to great depths, with few of the cloud features we had seen at Jupiter and Saturn. The *Voyager* encounter was our first opportunity to investigate the uranian weather systems. However, this was more difficult than many people imagine. The mission was not optimised for Uranus. When *Voyager* was launched in 1977, we would have been satisfied to successfully explore Jupiter and Saturn. Uranus is a bonus, and the atmospheric observations were made with aging instruments. However, we did make some amazing discoveries.

In violet and orange light, and in a red

Atmosphere of Uranus



ABOVE: By using different filters on Voyager 2's cameras, and by enhancing the contrast on the resulting images, scientists were able to discern subtle atmospheric banding centered on Uranus's pole of rotation. From left to right, these images were taken with the violet, orange and methane filters.

RIGHT: To the human eye, Uranus would appear as a hazy, featureless blue ball. Clouds lie deep within the atmosphere, so Voyager 2 was able to find only a few convective plumes, such as the white streak seen here near the limb of the planet. (The small doughnuts are artifacts due to dust in the camera.)
Images: JPL/NASA

wavelength absorbed by methane, Uranus displays definite structure in its clouds. In violet light, bands appear about the rotational pole, with darker bands at higher latitudes. In orange light the banded appearance contrasts with the violet image: The planet is darkest in the middle and low latitudes, with a bright band about halfway to the pole. At the methane wavelength, high clouds appear bright and low clouds dark. The mid-latitude band, where a thin cloud can be seen in the orange image, is free of the overlying haze layers that hang over much of the planet. We believe these high-level hazes are created photochemically and are composed of acetylene and ethane (C_2H_6) particles.

In these images, the planet does have a slightly banded appearance and clouds with a predominately zonal circulation, where winds blow in an east-west direction, rather than north-south. This circulation resembles the flow on Jupiter and Saturn. Thus, despite Uranus' tilt, the motions of its weather systems are zonal. So it is the rapid rotation of the planet, rather than the slowly changing distribution of solar heating, that organizes the weather systems.

Between 20 and 45 degrees latitude, where sunlight can penetrate to warmer levels, we saw a few discrete cloud systems, providing the first direct evidence of local motions in Uranus' atmosphere. These clouds are probably composed of methane particles, and resemble the convective plume clouds seen in the equatorial region of Jupiter. They are like the "anvil" clouds at the tops of thunderstorms on Earth, but enormously larger.

These clouds move in a westerly jet 40 to 160 meters per second faster than the planet's rotation period of 17.24 hours. The orientation of the plume tails and the positive direction of the winds relative to the interior suggest that the zonal wind velocity increases with altitude between 27 and 70 degrees south. This surprising conclusion contrasts with the winds expected from the temperature gradient. We can only assume that dynamical processes are creating a more complicated situation than our current theories can explain.

Atmosphere and Magnetosphere

The upper atmosphere provided plenty of surprises, too. A huge glow spreads outward about 50,000 kilometers. Before the *Voyager* encounter, the International Ultraviolet Explorer satellite had detected an intense signal first thought to be evidence of an aurora. However, we now think the signal is mainly due to an intense electroglow, a radiative process first seen at Jupiter and Saturn. The glow is generated by collisions between electrons and hydrogen molecules. This process, which may be driven by the coupling of atmospheric winds into the ionosphere, also dissociates hydrogen molecules. About half the resulting atomic hydrogen escapes and forms a corona extending out to Uranus' rings. As in other planets' outer atmospheres, evolution is still occuring today.

Garry Hunt is a member of the Voyager *Imaging Team. He is on The Planetary Society's Board of Advisors and is now with PA Computers and Telecommunications in London.*

An Ocean In Uranus?

by David Stevenson

We live on a planet where water dominates many aspects of our environment and lives. Liquid water forms our oceans, controls much of our climate and is the main constituent of living matter. Among the planets closest to the Sun — the terrestrial planets Mercury, Venus, Earth and Mars — only Earth has a water ocean today. Venus once had much more water than it has now (perhaps even in liquid form), and Mars has large amounts still, locked up in permafrost and ice caps, but the conditions required for water oceans seem rather restrictive.

Or are they? There is another very different world in which a water-rich ocean of a sort may exist. That world is Uranus.

Before I describe Uranus and some of the things we have learned from the *Voyager 2* flyby in January 1986, I need to explain some elementary facts about water. Under normal circumstances, water exists as both a condensed phase — solid or liquid — and as a vapor. For example, there are water molecules in the oceans on Earth and also in the air immediately above the oceans. We can talk about the ocean as a very well-defined thing because there is an abrupt change in behavior as we go from the medium just above the ocean (air with a little bit of water vapor) to the medium just below the sea surface (dense, almost pure water).

But suppose we carry out the following experiment: Take a closed, pressurized container in which some liquid water is placed. To begin with, the water is in the bottom with a little bit of vapor above the water surface. Now heat it up. As we do so, more water enters into the vapor; the water level drops and the pressure rises. Provided enough water is present, this process can be continued with the vapor becoming increasingly more dense as the pressure increases.

Eventually, at about 217 times the pressure at Earth's surface, and a temperature of about 370 degrees Celsius (700 degrees Fahrenheit), the vapor above and liquid below merge and become indistinguishable. This is called the critical point. At higher temperatures, there are no such things as liquid water and water vapor as separately identifiable forms of water, but simply a uniform, dense fluid. This fluid nevertheless has many of the characteristics we associate with fluids; in particular, it is dense enough that the molecules are packed quite closely together.

It seems likely that Uranus contains an enormous amount of water in this form. Since this water does not have a well-defined surface, because the critical point is exceeded, it is not an ocean in the way we usually apply that term on Earth. Nevertheless, it must profoundly affect the climate, chemistry and internal properties of Uranus in ways that may be similar to what would happen if there were an ocean with a sharp surface. Perhaps we should call it an ocean, provided we are careful about how that term is used. (The *Concise Oxford Dictionary* definition of ocean does not require that it have a surface!)

The evidence for this conjecture about Uranus is only indirect and not yet compelling, but it comes from a variety of observations including recent *Voyager* results. First, *Voyager* found that Uranus is rotating less rapidly than was previously thought, only once every 17.24 hours. When this information is combined with what we know about the gravity of Uranus, it implies that the material inside Uranus is not so centrally concentrated as was once thought. It is quite easy to construct a model (that is, a simplified mathematical description) of Uranus that satisfies these data and consists of just two layers: a rock core and an envelope consisting of a mixture of ices (mostly water, but also methane and ammonia) and gas (hydrogen and helium). The ices are hot and in the fluid form described above.

A second reason to favor this model lies in the complicated and large magnetic field discovered by *Voyager 2*. Although we have no detailed explanation of this field yet, it clearly requires significant electrical conductivity well out in the envelope of Uranus. Partial ionization of water (into H_3O^+ and OH^-) seems to be the only reasonable way to do this.

A third reason for this model lies in an older radio observation that there is less ammonia in the deep atmosphere of Uranus than expected. This can be explained by the fact that ammonia dissolves readily in water and is therefore extracted at even deeper levels by the water.

A fourth reason is more theoretical, but attractive, at least to this writer. It is the view that when a planet like Uranus formed, it suffered large impacts from bodies as massive as Earth. One of these impacts tipped Uranus on its side, into its present configuration. These traumatic events produced much stirring of the interior, and partly or completely homogenized the ice and gas, providing the simple structure described above.

Let us now take an imaginary ride in a submersible, down into the interior of Uranus. We begin in the atmosphere, where the temperature is very cold, −175 degrees Celsius (−350 degrees Fahrenheit), but sunlight still filters down. As we descend, through gas that is mostly hydrogen, the pressure and temperature gradually increase. At Earth-like temperatures, the pressure is hundreds of atmospheres (one atmosphere being the pressure at Earth's surface) and we are beginning to notice the presence of small amounts of water vapor and possibly water droplets (rain clouds). As we proceed deeper, the temperature, pressure and water content continually rise, but we never encounter a sharp surface that separates "atmosphere" from "ocean."

Eventually, at around 370 degrees Celsius (700 degrees Fahrenheit) and over a thousand atmospheres, the water content no longer increases: We are in a dense, well-mixed medium in which most of the mass is in the form of water (though the most common molecule is still hydrogen). At this stage we are only perhaps 800 kilometers below the "surface" of the planet (actually the hazy cloud layer high in the atmosphere that *Voyager 2* saw and that you see when you look at Uranus through a telescope).

As we proceed still deeper (and in total darkness, just as in the depths of Earth's oceans), the temperature continues to rise. There may be some interesting chemistry to observe, as yet poorly understood. The water begins to ionize more, becoming a poor but significant conductor of the electrical currents responsible for the observed magnetic field. Pressures become very large (millions of atmospheres) and the temperature reaches thousands of degrees, before we eventually encounter a rocky core, with a composition much like the inside of Earth. This would occupy the innermost 5,000 to 8,000 kilometers of Uranus, which has a radius in excess of 25,000 kilometers. Down here, water has a density three times greater than the water coming out of your faucet. It is an excellent electrical conductor, it is probably opaque, and the special type of chemical bonding (called hydrogen bonding) that makes water behave as it does on Earth has now been totally destroyed. This bizarre water is 10,000 times more abundant in the solar system than the water we know and love on Earth!

Why does any of this matter? Aside from being fun (an important factor for most scientists), an understanding of Uranus and its water ocean helps us to understand how planets form and evolve. If we can figure out how the water is distributed in Uranus then we may have a better idea on how to explain the magnetic field, the atmospheric winds and even whether Uranus suffered large impacts in its infancy. Regrettably, it may be a long time before another spacecraft visits Uranus, but in the meantime there are some exciting and challenging intellectual puzzles for us to solve.

David Stevenson is a professor of planetary science at the California Institute of Technology. His main interest is in the formation and structure of planets.

On to Neptune!

by Ellis D. Miner

A Grand Tour of the giant outer planets, once an "impossible" dream of advanced mission planners at the Jet Propulsion Laboratory, is now a three-quarters completed reality. That hardy denizen of deep space, *Voyager 2*, followed *Voyager 1* through spectacular encounters with Jupiter and Saturn. Then, forging into virgin territory, *Voyager 2* (see the March/April 1986 issue of *The Planetary Report*) became the first spacecraft to visit a planet unknown to the ancients — Uranus. In the July 4 issue of *Science*, the 11 *Voyager* science teams reported their preliminary findings.

Voyager 2 will complete its Grand Tour when it encounters Neptune in the summer of 1989. *Voyager* personnel are now busily preparing a detailed sequence of science observations for the four months from early June to the end of September. The encounter is divided into four phases: a nine-week observatory phase, a two-week far encounter phase, a five-day near encounter phase, and a five-week post encounter phase. *Voyager 2* will probably make its closest approach to Neptune on August 25, 1989. If necessary, this time can be shifted a day earlier or later.

What will Voyager 2 find when it reaches the neptunian system? The planet's large moon, Triton, will be a prime target for the spacecraft. Methane ice, condensed out of a nitrogen-methane atmosphere, may coat the terrain. Triton is so cold that nitrogen lakes or oceans may spread across its surface.

Painting: Ken Hodges for JPL/NASA

The Planet

Although Neptune is nearly a twin to Uranus in size and color, the two planets differ considerably in their other characteristics. Neptune's axis of rotation is modestly tilted only 29 degrees to the plane of its orbit around the Sun; Uranus is tilted 98 degrees! Neptune receives less than half the sunlight Uranus does, but it's at nearly the same temperature, implying that at least half the heat radiated by Neptune comes from its interior.

Another feature Neptune doesn't share with Uranus is possibly related to this internal heat source: Neptune's atmosphere is quite variable, and broad atmospheric features have been tracked for hours and even days. By clocking these features, scientists have estimated Neptune's rotation period to be near 18 hours. No uranian cloud features are discernible from Earth; the 17.24-hour rotation period determined by *Voyager 2* replaced a previous best estimate of 15.6 hours.

Neptune orbits about 30 Astronomical Units from the Sun (one AU is the average distance of Earth from the Sun), as compared with 19 AU for Uranus. Because of its greater distance, Neptune takes 165 years to travel around the Sun, nearly twice the 84-year orbital period of Uranus.

The Satellites

The satellites of the two planets may also be very different. Uranus has a well-behaved system of at least 15 moons, all with nearly circular prograde orbits (moving in the same direction as the planet's spin) at low inclination relative to the planet's equator. In contrast, Neptune's Nereid follows the most eccentric orbit of any natural satellite in our solar system. Both Nereid and Triton, Neptune's largest satellite, travel orbits highly inclined to the planet's equator. And Triton is the only Moon-sized satellite in our solar system that orbits in a retrograde direction.

Triton is different in another way. Telescopic observations suggest that methane ice lies on its surface, with shallow lakes of liquid nitrogen enlivening the landscape. Some calculations suggest that Triton's atmosphere may change seasonally by as much as a factor of 1,000, varying from 1/10,000 to 1/10 Earth's atmospheric pressure at sea level. When *Voyager 2* reaches it, Triton's surface pressure is expected to be between these two values, rising toward the maximum. Triton may be the only satellite whose atmosphere is substantial, yet transparent enough to reveal its bizarre surface to spacecraft instruments.

The Rings

Over the past several years, scientists have tried to detect a neptunian ring system by monitoring the apparent brightnesses of stars as the giant planet passes in front of them. About 10 percent of these occultations show tantalizing decreases in brightness that may indicate material in orbit about Neptune: A series of discontinuous ring arcs may circle the planet.

Voyager personnel are concerned because a scientifically desirable spacecraft trajectory carries *Voyager 2* through Neptune's equatorial plane uncomfortably close to the possible ring arcs. Although the chances of hitting one are thought to be less than one in a hundred, alternative trajectories are being studied. The trajectory could be "tweaked" as late as one week before the August 25 arrival date.

The Challenges

As *Voyager 2* travels farther and farther from the Sun and Earth, light levels drop and radio communication becomes more difficult. *Voyager* engineers have been remarkably successful in devising ways to reduce image smear and to provide the capability for longer camera exposures. The image smear rate has been reduced, permitting us to obtain more unsmeared images using the same exposures as we did for smeared pictures at Saturn. However, the longest exposure (without the use of the tape recorder) at Uranus was 15 seconds. For Neptune, normal exposures of up to 61 seconds are now possible, and long exposures of →

multiples of 48 seconds are also possible without the tape recorder.

Deep Space Network tracking station efficiencies are being increased and, for the first time, the Very Large Array of radio telescopes in New Mexico will help track the spacecraft. To track *Voyager* over the western Pacific, the Canberra Deep Space Network tracking stations will be helped by the Parkes radio telescope in Australia and by the Usuda tracking station in Japan.

Voyager signals, transmitted with only 23 watts of radio power from Neptune's distance of nearly 4.5 billion kilometers, will take four hours to reach Earth. Because the eight-hour round trip light time will exceed the duration of a tracking pass at a single station, precise measurements of *Voyager*'s distance must be made by transmitting a ranging signal from one station and receiving the return signal at another station a third of the way around Earth.

At Neptune, *Voyager 2* will again use new data techniques first used during the Uranus encounter. Onboard computers will compress imaging data so only two-fifths as many bits per picture need be transmitted. Automatic responses to several possible problems have been programmed into the computer. For example, if the one remaining radio receiver were to fail, a backup mission would automatically be executed, and rudimentary data about the neptunian system would still be transmitted to Earth.

For a spacecraft designed and built back in the days when hand-held calculators were first being marketed, the *Voyagers* have been remarkably responsive to the science and engineering demands placed on them.

Beyond the Planets

The *Voyager* spacecraft are powered by radioisotope thermoelectric generators (RTGs) whose power output decreases about seven watts per year. At that rate, and barring catastrophic failures of critical spacecraft electronics, *Voyagers 1* and *2* should continue transmitting valuable data until at least 2010. By then, both spacecraft should have penetrated the outer boundary of the Sun's magnetic field (the heliopause) where the flow of high-energy charged particles from nearby stars will stop the outward flow of the solar wind, enabling scientists to measure the interstellar environment for the first time.

In a sense, however, the mission of these two *Voyagers* may not end for thousands or even hundreds of thousands of years, as they, with their cargos of gold records, prepared by Planetary Society President Carl Sagan and his co-workers, and carrying the sights and sounds of Earth, sail ever outward through the realm of the stars.

Ellis Miner is Deputy Project Scientist for the Voyager *Project.*

Exploring the Uranian Satellites

(continued from page 7)

Extensive regions of smooth terrain look as though some highly viscous material, possibly water ice mixed with ammonia and methane, slowly filled in the large valleys that apparently resulted from crustal tearing. Some half-buried craters in the same area suggest that viscous material extruded onto the surface and flowed into them. When we counted craters in the smooth terrain, we found that it is younger than surrounding areas, hinting that Ariel's interior was active in the past. Ariel has the brightest surface of the uranian satellites, further suggesting that Ariel renewed its surface in the distant past.

Miranda

Years ago when I was sweating out my dissertation defense, a particularly appropriate but (luckily) unasked question would have been: "If you could direct *Voyager* to fly closest to the most interesting uranian satellite, which would it be?" I would have answered: "Oberon or Ariel, but not Miranda because it is too small to have been geologically active. It's probably just a boring, heavily cratered ball of ice and rock."

As it turned out, I would have been wrong. Miranda displays a bewildering array of landforms unlike anything we have ever seen. On opposite sides near its equator are two huge oval features, nicknamed "circi maximi" because they resemble an ancient Roman chariot-racing track. Both circi maximi extend about 300 kilometers along the equator, while their other dimensions are unknown because they extend over the edge of the visible disk. The ovoids, as they were later called, are marked with complex fault and ridge systems laid out in a remarkably symmetric fashion — they look almost artificial.

Near the south pole is a smaller trapezoidal feature, nicknamed the "chevron," with similar parallel faults and ridges. On the terminator (the line between day and night) near the equator, a huge cliff looms nearly 20 kilometers high. We estimated that, in Miranda's low gravity, it would take almost 10 minutes to fall from the cliff to the valley floor below. That cliff was evidently formed by a fault that runs across the entire southern hemisphere and probably into the unexplored northern hemisphere.

We were also treated to images of hummocky terrain that looked suspiciously like the very old highlands of Earth's Moon. Crater counts tell us it is probably the oldest terrain on Miranda. The ovoids seem to have grown at the expense of this old terrain.

It's tempting to speculate on how Miranda became one of the most interesting and geologically complex objects in our solar system. We rejected many trial scenarios before settling on one we now think is plausible. If we can apply knowledge of cratering rates from the jovian and saturnian satellites to the uranian satellites, then Miranda should have suffered impacts large enough to break it apart several times. The debris would stay roughly in its old orbit and quickly reaccrete to form a new Miranda. We also know that ice, even though it is solid, will slowly deform under its own weight over thousands and millions of years. Therefore, if large blocks of rock and ice remained warm and mixed haphazardly in Miranda, then as rock slowly sank to the core while ice flowed plastically to the surface, patterns might be produced that would look similar to what we see on Miranda today. In an alternative view, the ovoids and chevron may be surface manifestations of large, viscous, rising plumes of ice made buoyant by heat from radioactive decay in Miranda's interior.

Intriguing Experiments

Whatever mechanisms produced the bizarre geology on Miranda, or any of its sibling satellites, clearly the uranian satellites are yet another of nature's intriguing experiments in satellite formation. Part of the challenge of understanding them will be to determine how they are related to the jovian and saturnian satellites.

For example, the *Voyager* data suggest that the uranian satellites are more dense than their saturnian counterparts. What does this difference imply about how the two systems formed? Or why are the uranian satellites darker than the saturnian ones, when the major members of both systems are mostly composed of water ice?

These are only two questions that can be addressed with *Voyager* data, and with data from planetary probes as yet unlaunched or unbuilt. Perhaps 20 years from now, when the Sun will be over Uranus' equator, a spacecraft named *Herschel* will orbit Uranus and return spectacular images of both hemispheres of the planet and its satellites.

In the meantime, fitting the jovian, saturnian and uranian satellites into a picture of how satellites form and evolve will remain an important challenge to planetary scientists. And, in 1989 we will be confronted with new mysteries when *Voyager 2* explores Neptune and its satellites. I can hardly wait! And I wish Herschel and Kuiper could be there with me.

Robert Hamilton Brown is a planetary scientist at the Jet Propulsion Laboratory. His main fields of study are asteroids and satellites in the outer solar system.

SOCIETY *Notes*

LOOKING AHEAD . . .

. . . to Planetary Society activities in the coming months. We will be participating in several events already planned for 1987, including:

January 4, 1987. The American Astronomical Society meeting in Pasadena, California, at the Pasadena Convention Center.

February 14-19, 1987. The annual meeting of the American Association for the Advancement of Science, in Chicago. The Planetary Society is hosting a luncheon at the Palmer House on Sunday, February 15. We will also have a booth in the exhibit hall in the Hyatt Regency Hotel, 151 E. Wacker Drive. Chicagoland members should look to the mail for details, or call the Society's information line.

March 16-20, 1987. The annual Lunar and Planetary Conference in Houston. The Society is sponsoring a public symposium on planetary exploration in the United States and the Soviet Union.

July 18-21, 1987. The Strategy for Mars conference in Boulder, Colorado, cosponsored by The Planetary Society and the American Astronautical Society.

Details of Society events are always available on our information lines. From west of the Mississippi, call 818/793-4294; from east of the Mississippi, call 818/793-4328.

SEDS STUDENT MEMBERS

We have made a special arrangement for members of the Students for the Exploration and Development of Space (SEDS) to become student members of The Planetary Society for a special reduced rate. SEDS sponsors educational programs, conferences and projects to interest high school and college students in space-related careers and to support space exploration. With this program, The Planetary Society can expand its educational services to students on many campuses around the United States and Canada. This program is made possible by the Society's Education Fund, created by our members' donations.

Students who wish to join SEDS may write Gregg Berman, SEDS, Room W20-445, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139.

NEW ASTEROID DISCOVERIES

Eleanor Helin, Planetary Society Asteroid Project leader, and her colleague A. Maury discovered four near-Earth asteroids last summer during the Palomar Sky Survey II. The asteroids, dubbed 1986LA, 1986NA, 1986PA and 1986RA, were found with the 48-inch Schmidt telescope at the Mount Palomar Observatory. Asteroid 1986PA is especially interesting because its orbit crosses the orbits of both Earth and Venus.

The Palomar Sky Survey II uses new technological advances in types of emulsion and sensitizing procedures to photograph the northern hemisphere sky. It will replace and improve sky prints from Sky Survey I, done from 1949-1956, by recording fainter objects than was possible in the earlier survey.

Mrs. Helin's Asteroid Project is partly funded by members of The Planetary Society, in a cooperative program with NASA and the World Space Foundation.

MEMBERS HELP SOCIETY

Planetary Society members have found some imaginative ways to contribute to our efforts.

Steve Arthurton of Midwest City, Oklahoma has donated $50.00 each month to the Society over the past two years. Mr. Arthurton hopes that the Society "will grow and prosper so that it might become a force to reckon with in establishing space goals and policies."

Timothy Stowe, 15, of Silver Spring, Maryland recently wrote all 100 United States senators to support a joint US-Soviet mission to Mars. While 24 senators responded, only 10 letters dealt specifically with Mr. Stowe's letter. Senators Proxmire, Specter, Dodd, Biden, Harkin, Thurmond, Glenn, Moynihan and Danforth expressed interest in the issue. Efforts like Mr. Stowe's help decision-makers understand the significance and popularity of space exploration as a motivation for a positive future.

James A. Frey of Arizona made a bequest to The Planetary Society in his will. His contribution will be a lasting legacy for future generations interested in space exploration. We thank Mr. Frey for his foresight and support of the Society's goals.

If you would like to join Mr. Frey in building a future for humans in space, write to The Planetary Society, Planned Giving, 65 N. Catalina Avenue, Pasadena, CA 91106.

Arthur C. Clarke Becomes Advisor to Society

The Planetary Society is pleased to announce that Arthur C. Clarke has joined its Board of Advisors. As one of the founders of the British Interplanetary Society, as the inventor of the geosynchronous communication satellite, as a world-renowned author of science fiction (*2001: A Space Odyssey*) and nonfiction (*Interplanetary Flight*), Mr. Clarke has made major contributions to the dawning of the space age. An appreciation of his work appeared in the May/June 1983 *Planetary Report*. Mr. Clarke is currently Chancellor of the University of Moratuwa in Sri Lanka and lives in Colombo.

SWEDISH MEMBERSHIP GROWS

The Planetary Society has dramatically increased its membership in Sweden, thanks to a recruiting effort by the Swedish Space Movement, coordinated by Society member Hans Starlife. Our Swedish contingent now numbers 99 and is still growing. We salute members of the Swedish Space Movement for their dedication and enthusiasm.

MARS CONTEST WINNER

The Planetary Society is pleased to announce the winner of its 1986 Mars Institute Student Contest. Michael P. Scardera, a graduate student at the University of Maryland, won with his paper, "A Ground-Roving Vehicle and a Rocket Transport Based on Liquid Carbon Monoxide-Liquid Oxygen for Transportation Over the Surface of Mars." Mr. Scardera won $1,000.00 and an all-expenses-paid trip to NASA's Mars Conference, held last July in Washington, DC.

This year's contest entrants were asked to design a transportation system for exploration of Mars from a research base. According to Dr. Christopher McKay, coordinator of the Mars Institute, the papers submitted approached this design challenge from a variety of perspectives. Proposed vehicles included rovers, balloons, rockets and air-cushioned craft.

Mr. Scardera's ground rover and rocket transportation system was powered by liquid oxygen and liquid carbon monoxide because these materials can be extracted from the martian atmosphere. The rover, with a range of 450 kilometers, carried a rocket capable of either ballistic or hovering flight, which could explore the entire surface of Mars.

The 1987 Mars Institute Student Contest will be announced in the January/February *Planetary Report*.

News & Reviews

by Clark R. Chapman

I remember in mid-1980 when *Science* published a lengthy article by Luis Alvarez and others, announcing the discovery of an iridium-rich layer of fossil clay in northern Italy. The specific findings were interesting, but the conclusion — proclaimed later in the popular press — that an asteroid impact caused the extinction of dinosaurs and other species at the end of the Cretaceous period of geologic time . . . well, it didn't strike me as particularly new or remarkable. After all, I'd heard it all before and, of course, I thought it *was* probably the explanation for the extinctions.

This was not, however, the initial attitude of University of Chicago paleontologist David Raup, who as a referee for the editors of *Science*, had received the Alvarez manuscript several months earlier. As he reports in his book *The Nemesis Affair* (W. W. Norton & Co., New York, 1986), at first he actually checked the box on the review form labeled "mediocre . . . should not be published." One can credit Raup, however, with seeing the paper's potential, saying so despite his misgivings, and helping to get a revised version into print within a few months.

For a scientist like myself who has studied pictures of crater-scarred surfaces of planets from Mercury to the satellites of Jupiter (and now beyond), and who has thought about the thousands of asteroids and comets hurtling through space, the inevitability of catastrophic impacts on our own planet seemed obvious. For years, geologists had been discovering large terrestrial craters from aerial photographs, and had confirmed the impact-origin of dozens of them by on-site investigations. I would have thought that any intelligent lay person, familiar with TV news pictures from our space probes, would have immediately said, "Sure, an asteroid impact wiped out the dinosaurs 65 million years ago . . . why not?" But some very smart paleontologists to this day discount the idea as difficult to fathom. David Raup's book provides us with some insight as to why.

Raup is a paleontologist, and he helps us see the Alvarez idea from the intellectual perspective of a classical geologist, who is a product of education and training that has hammered home the idea that geologic change takes place slowly, uniformly, and by the relentless action of processes we can witness every day of our lives. We owe the existence of modern geology to the successful struggle the geologists' predecessors waged against a religiously inspired view of Noachian floods and other divine catastrophes wrought upon the face of our planet. To let random thunderbolts from outer space re-emerge as the major forces shaping the evolution of our planet's surface and biosphere would fly in the face of the battles won long ago.

Raup, himself, is no ordinary paleontologist. He is a quantitative scientist immersed in a qualitative field. In recent years, he has promoted an even stranger idea: that the supposedly random shooting gallery of asteroids and comets isn't random at all, but instead that "comet showers" occur periodically every 25 or 30 million years. This idea — ascribed to "Nemesis," a stellar companion of the Sun — has had its ups and downs, and Raup himself admits that the story of his book is incomplete.

As an account by a scientist deeply involved in this grand debate linking astronomy, planetary science, geology, geochemistry, paleontology, environmental sciences, biology and maybe even history, this book is well worth reading. I was surprised, however, by the relatively minor role that planetary science plays in Raup's account. For a planetary perspective on the role of rocks from space, I recommend another article as supplementary reading: Ken Weaver's nicely illustrated account of asteroids, comets, meteorites and meteor craters in the September 1986 *National Geographic*. One cannot read Weaver's account of modern meteoritics and not be impressed with the inevitability of impacts on Earth.

A final supplementary piece, just to bring everything up-to-date, is in a more obscure publication called *Eos*, a news sheet filled with a motley assortment of items published by the American Geophysical Union. The September 2 *Eos* contains a chatty, very readable summary of the current state of affairs in the dinosaur wipe out business by one of the original advocates of the idea, geologist Walter Alvarez. He provides a first-person account of the original studies in northern Italy, and demolishes the lingering arguments of stubborn paleontologists who still cling to the idea that anything but an asteroid is a better idea for explaining mass extinctions.

Clark R. Chapman, who in August co-organized an international conference about the planet Mercury, wrote the Mercury essay in the Byron Preiss fact/fiction book, The Planets.

Origin of the Moon

One of the most intriguing mysteries in planetary science is the origin of Earth's Moon. The subject of speculation and legend over centuries and of scientific analysis for more than 100 years, this puzzle remains unsolved. Did the Moon come out of Earth? Did it and Earth form together in a cloud of gas and dust around the proto-Sun? Or did it wander to Earth from elsewhere?

Stimulated by the prospect of putting the problem away by direct measurement, scientists of the space age have made great efforts to explain the Moon's beginnings. The latest of their findings are described in a big and highly technical book, *Origin of the Moon*, edited by W.K. Hartmann, R.J. Phillips and G.J. Taylor and published by the Lunar and Planetary Institute in Houston. The book contains and extends discussions from a major 1984 meeting on the subject, and it is a splendid, modern compilation of ideas and data.

As one reads along, often in low gear to cope with pages dense in scientific language and the close reasoning of specialists, one comes to understand the fascination of the puzzle: There is the Moon, serenely sailing in its precisely known orbit, with much of its geology and chemistry now clearly understood, but we have yet to figure out how it got there.

Because the *Apollo* moonrocks showed the Moon's material to be in some ways similar to the material of Earth's mantle (which underlies Earth's crust) theories that make the Moon largely out of Earth matter have received a boost. At the same time, careful mathematical analyses have been making it seem more and more unlikely that the Moon formed elsewhere, wandered by and was captured into orbit about Earth. And the hypotheses involving formation of Earth and the Moon side-by-side in a swirling cloud of gas and dust seem to be running into increasing difficulties, both chemical and dynamical. Another picture, combining elements of previous theories (some of them dating from the 19th century) has emerged as a likely prospect. In this concept, the Moon's birth was a smashing event: Near the end of the epoch of planetary accretion, some 4.6 billion years ago, Earth was struck a glancing blow by an object the size of Mars. A huge quantity of material was splashed out and some of it was driven into Earth orbit by the exploding gases, there to form a ring of debris that coalesced into the Moon. Although many details remain to be tested, this hypothesis has become popular among scientists — in part because of the increasing implausibility of other explanations.

Perhaps we will never know. But when spacecraft return to the Moon, one of their objects will be to continue to search for clues to this mystery. — *JAMES D. BURKE*

World Watch

by Louis D. Friedman

WASHINGTON — NASA has announced a new schedule for space shuttle launches. The space agency is planning to resume shuttle flights in February 1988. Five launches are planned for that year, with 10 in 1989 and 11 in 1990. All the scheduled launches will be from Cape Canaveral; the opening of the western launch center at Vandenberg Air Force Base has been delayed until 1992.

The shuttle fleet is getting out of the commercial launching business, except for a few commercial satellites still under contract. It will now be used only to launch military and scientific payloads. U.S. commercial users will be forced to switch to yet-to-be-developed private launch vehicles or to contract with foreign agencies for launch services.

The new shuttle schedule officially lists only "planetary opportunities," without naming the spacecraft, for November 1989, October 1990 and the fourth quarter of 1992. NASA officials have explained that these "opportunities" could be launch slots for either *Galileo* or *Ulysses*, the European solar polar mission. But launch in October 1990 could not take *Galileo* on a trajectory bound for Jupiter. And the Mars Observer, once scheduled for launch in August 1990, seems to have been forgotten.

Dr. Burton Edelson, NASA Associate Administrator for Space Science and Applications (and long-time Planetary Society member) has told the Society that the decision to delay the Mars Observer has not been made. Although the Space Science office did consider delaying the mission for two years for budgetary reasons, Dr. Edelson said they have reconsidered the delay and are now still planning an August 1990 launch for the Mars Observer. (This reconsideration was partly the result of efforts by many Planetary Society members who contacted the congressional committees that oversee NASA's budget.)

Dr. Edelson did note, however, that, because of the problems of fitting four planetary launches (*Magellan*, *Ulysses*, *Galileo* and the Mars Observer) into two years (1989-90), all planetary launch plans will be reviewed in January 1987. One solution would be for NASA to launch *Galileo* on a *Titan 4*, an expendable launch vehicle (with a *Centaur* upper stage) being developed by the Air Force. This new vehicle will not be ready until 1991, but its superior capability would get *Galileo* to Jupiter at the same time as a shuttle launch in 1989. Space scientists have been urging NASA to use expendable launch vehicles as well as the shuttle, and to launch all four planetary missions in 1989-90.

Dr. Edelson also told us that, although the Comet Rendezvous Asteroid Flyby (CRAF) mission was not likely to get a "new start" in 1988, he would program funds to keep it alive. However, mission scientists say the planned amounts are too low.

"Planetary missions have been hurt more than anything by the launch vehicle problems since the *Challenger* tragedy," Dr. Edelson said, "and I consider getting that program back on track as the first priority of my office." We will keep Society members informed as this situation develops.

INNSBRUCK — The International Astronautical Federation (IAF) held its annual congress here October 5-10 on the theme "Space: New Opportunities for All People." The public was invited to a display center filled with over 50 exhibits, from large displays by the European, Japanese, French and Soviet space agencies and companies to a small one by The Planetary Society. NASA didn't provide an exhibit. At the meeting, the Society became one of the first popular organizations to join the professional federation.

Scientists presented results from the Halley's Comet missions, both the European Space Agency and the Soviet-led Intercosmos organization displayed models of the comet's nucleus, and the Soviets provided an in-depth look at their *Mir* space station. Mars exploration was discussed in a special session, with Society Advisor Jacques Blamont presenting a new concept for exploring the Red Planet by balloon. A balloon using both helium and hot air could fly by day and land every night at a different spot. Both the upcoming Soviet *Phobos* mission and the U.S. Mars Observer missions were discussed at the session. Society Advisor Roald Sagdeev, V. Linkin and I presented a paper on the possibilities for international cooperation in Mars exploration.

Two special symposia were held on the Search for Extraterrestrial Intelligence (SETI). Both the strategy of the search and the problem of what to do if a signal is found were discussed.

The IAF is a particularly important organization for it provides contact with space interests outside the major spacefaring nations, including those in the Third World. The Planetary Society joined the IAF as an international member, citing our goal of bringing together public and professional interests throughout the world.

Louis Friedman is the Executive Director of The Planetary Society.

FLIGHT NUMBER	DATE	ORBITER	PAYLOAD
26	2/18/88	**Discovery**	Tracking and Data Relay Satellite C
27	5/26/88	**Atlantis**	Department of Defense payload
28	7/28/88	**Columbia**	Department of Defense payload
29	9/22/88	**Discovery**	Tracking and Data Relay Satellite D
30	11/17/88	**Atlantis**	Hubble Space Telescope
31	1/19/89	**Columbia**	Astro-1 experiment package
32	3/2/89	**Discovery**	Department of Defense payload
33	4/25/89	**Atlantis**	*Magellan* spacecraft
34	6/2/89	**Discovery**	Department of Defense Spacelab
35	6/21/89	**Columbia**	Two Global Positioning Satellites and the Materials Science Laboratory 3
36	7/20/89	**Atlantis**	Department of Defense payload
37	9/1/89	**Discovery**	Department of Defense payload
38	9/21/89	**Columbia**	Two Global Positioning Satellites and the Materials Science Laboratory 4
39	11/1/89	**Atlantis**	Planetary Opportunity
40	12/7/89	**Discovery**	Space Laboratory — Life Sciences 1
41	1/18/90	**Columbia**	Gamma Ray Observatory
42	2/15/90	**Atlantis**	Department of Defense payload
43	4/20/90	**Discovery**	International Microgravity Laboratory 1
44	5/4/90	**Columbia**	Global Positioning Satellite Pathfinder (Stategic Defense Initiative experiment), Electrophoresis Operation in Space 1, Space Station Heat Pipe Advanced Radiation Experiment
45	5/31/90	**Atlantis**	Department of Defense payload
46	7/12/90	**Discovery**	Department of Defense payload
47	7/26/90	**Columbia**	Global Positioning Satellite 6, Skynet communications satellite 4, Materials Science Laboratory 5
48	8/31/90	**Atlantis**	Department of Defense payload
49	10/5/90	**Discovery**	Planetary Opportunity

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