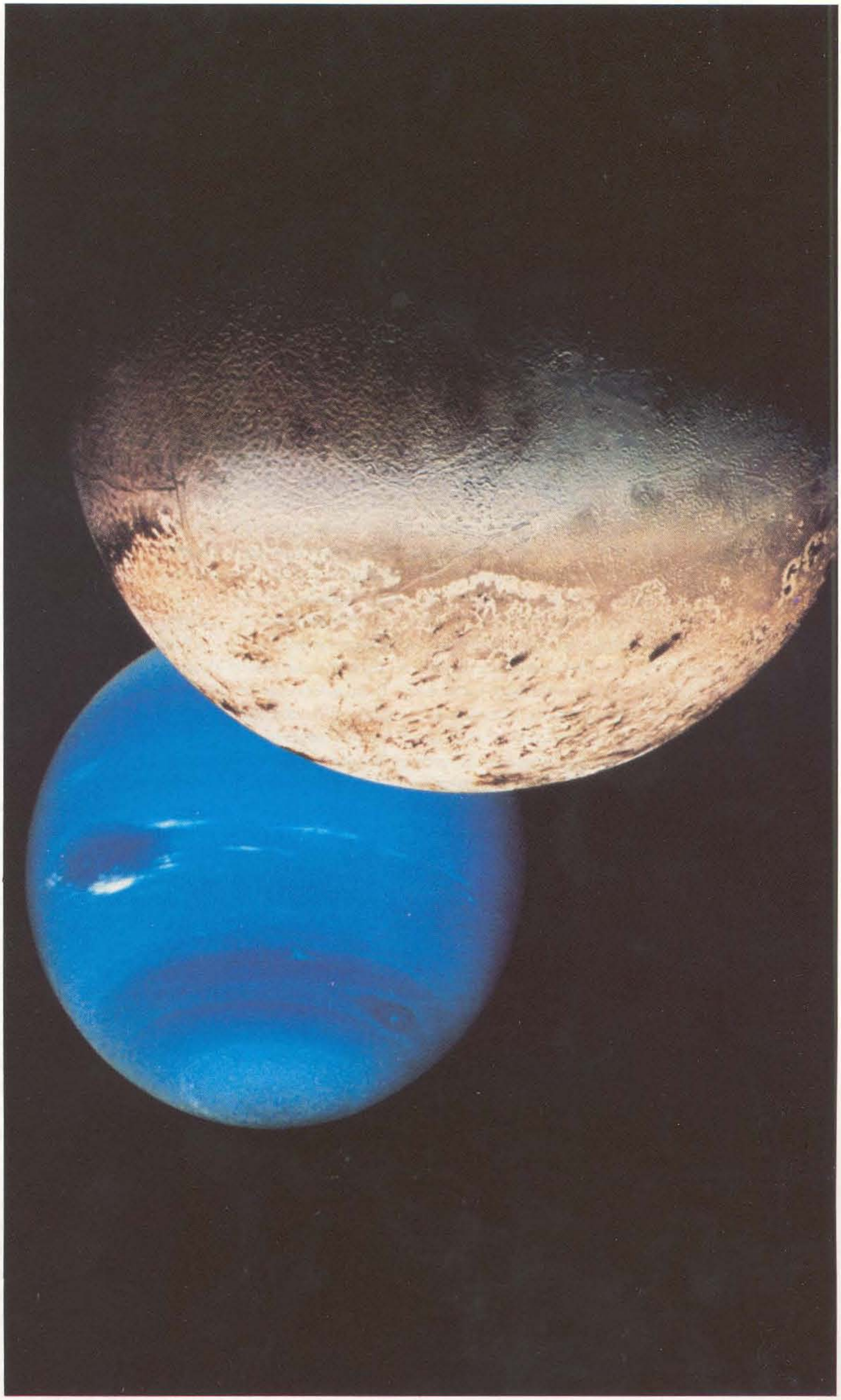


Voyager at Neptune

by Edward C. Stone

Voyager revealed to us a solar system with distinctive worlds of unexpected richness and diversity.

A mosaic of Voyager images shows blue-green Neptune behind the south polar region of its moon Triton.

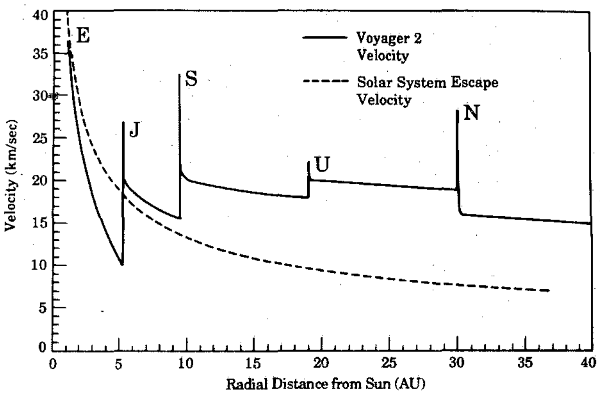
Late last August Voyager 2 flew by Neptune, the most remote object yet visited by a spacecraft and the culmination of a 12-year journey of exploration of the four giant planets. In a real sense Voyager has been writing the encyclopedia of the outer solar system over that last 12 years. For the latest volume I'd like to describe what we discovered last August, what we now understand, and what still puzzles us.

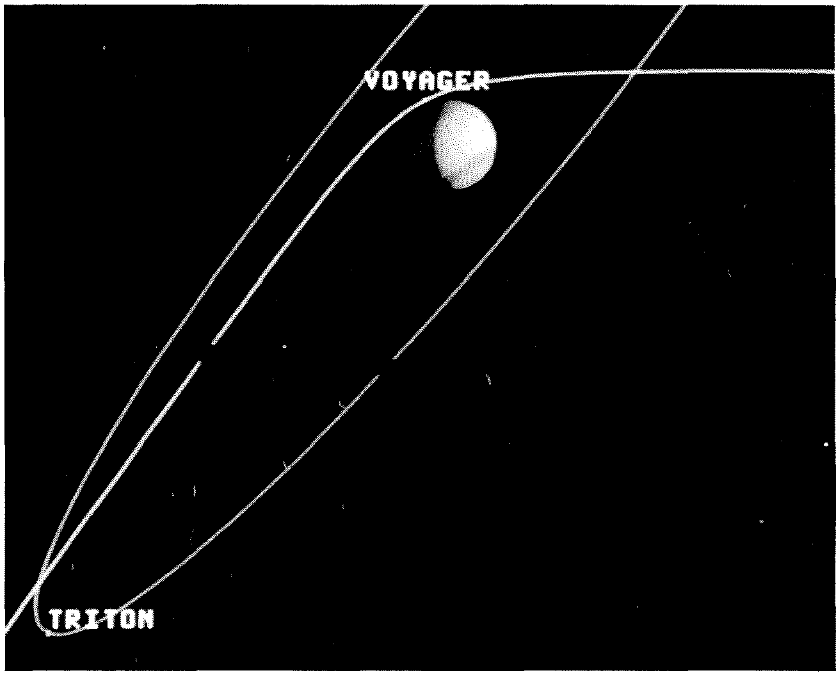
The journey to the outer planets is long because of the great distances involved. Earth, which is one of the inner four small, rocky planets, is one astronomical unit (AU) from the sun—almost 100 million miles. Of the outer giant planets, Jupiter is about 5 AU from the sun, Saturn 10, Uranus 19, and Neptune 30. When the two Voyager spacecraft were launched in 1977, Voyager 1 was on a faster trajectory. After its encounter with Jupiter, it flew by Saturn in such a way that it would, as seen from Earth, veer behind Saturn's large moon Titan as well as behind the rings, so that we could study these two important aspects of the Saturnian system. The geometry of this flyby meant that Voyager 1 would head upward out of the plane of the planets, unable to encounter any other bodies. But having accomplished those two key objectives with Voyager 1, we could leave Voyager 2's trajectory in the plane of the planets, headed toward an encounter with Uranus in January 1986 and finally Neptune in August 1989.

The planetary alignment that made this possible happens once every 176 years, but more than just the proper alignment was necessary to complete the voyage. We used the slingshot effect of flying by each of the giant planets to boost the spacecraft on to the next one. When we launched Voyager, there was enough energy from the Titan III Centaur launch rocket to almost—but not quite—reach Saturn. It was only because the Jupiter flyby gave the spacecraft as big a kick as the launch vehicle itself that Voyager had enough energy to reach Saturn. Saturn and Uranus gave Voyager 2 additional boosts, enabling it to reach Neptune in just 12 years rather than 30.

Designing a spacecraft for exploring the outer planets was also a challenge. Voyager was built and is operated by the Jet Propulsion Laboratory, which is managed by Caltech for NASA. Because the spacecraft was designed in the early and mid-seventies, much of its technology is now outdated. Although its computers have performed well, their memories are small compared with the million-byte memories in today's personal computers. For example, the computer used to control the sequences of in-flight operations has a memory of only 8,000 words. The spacecraft is powered by radioisotope thermoelectric generators using plutonium 238, which provide about 7,000 watts of heat that is converted to about 400 watts of electrical power using thermocouples—a very rugged, durable power supply. The sunlight in the outer solar system is much too feeble for solar panels to provide enough power.

Voyager was designed for a particular mission—a four-year journey to Jupiter and Saturn. To extend the journey to Uranus and



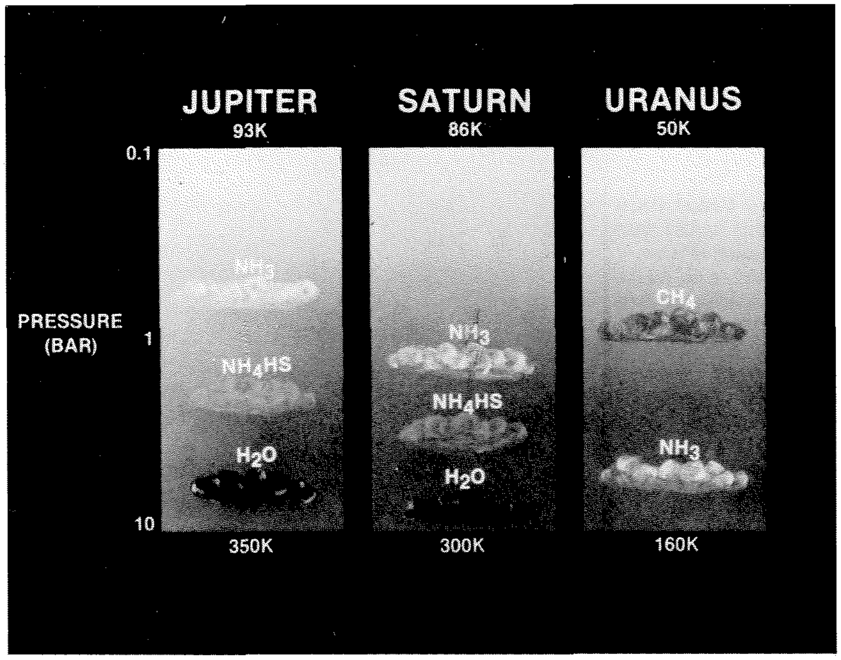


Top: Each of the planets on Voyager's Grand Tour supplied a slingshot boost to propel the spacecraft on to its next encounter. Bottom: From nearly 3 billion miles away, JPL engineers guided Voyager to within 3,000 miles of Neptune, bending its trajectory sharply to intersect Triton's orbit and fly behind Neptune's large moon.

We were able to investigate the differences in the planets progressively farther from the sun.

Neptune we had to extend the reach of Voyager three times farther than originally designed. That required a number of changes in the software of the spacecraft, changes that were actually made only *after* Saturn. For example, in order for the craft to be able to take images with exposures 10 minutes long in the decreasing light farther out (sunlight at Neptune is only about 1/900th of what it is on Earth), we had to stabilize the spacecraft much more precisely than was necessary at Saturn. This was a major engineering achievement accomplished by JPL engineers after the Saturn encounter. Also, the radio signal coming back from Neptune was only 1/9th as strong as that from Saturn, which is three times closer. So the JPL-run antennas, which are located at three sites around the world, were enlarged from 64 meters to 70 meters, and we borrowed one 64-meter antenna from the Australians and another from the Japanese. We also made use of the 27 antennas of the Very Large Array (used for radio astronomy) in the high desert of New Mexico. With a receiver on each antenna, the VLA acted as a single large antenna, which was electronically coupled to the 70-meter antenna in Goldstone to detect the very feeble signal Voyager was sending back. We had to press the capability of the spacecraft and the ground system to their very limits in order to capture the information coming back from the edge of the solar system.

Another challenge was the very close flyby that we had planned—guiding Voyager over the north polar region of Neptune a mere 3,000 miles above the cloud tops, where the spacecraft



Water clouds form in Jupiter and Saturn's atmospheres; clouds of ammonium hydrosulfide overlie that layer, with the top clouds composed of ammonia ice crystals. On Uranus (and on Neptune), where it's much colder, the ammonia clouds form deep in the atmosphere. The topmost cloud deck is made of frozen methane.

was deflected sharply downward to an encounter with Triton. We wanted to fly behind Triton so that we could look at the sun setting through Triton's atmosphere and watch the radio signal disappear. To do so required remarkably precise navigation from nearly 3 billion miles away. For one critical measurement of the atmosphere, we needed to know to within one second when the spacecraft was to arrive at a particular point. This was much more accurate timing than we had ever attempted before—and it worked. Because of these and similar improvements we were able to investigate the differences in the planets progressively farther from the Sun. And we can interpret those differences to help sort out how the solar system formed 4½ billion years ago.

Temperature

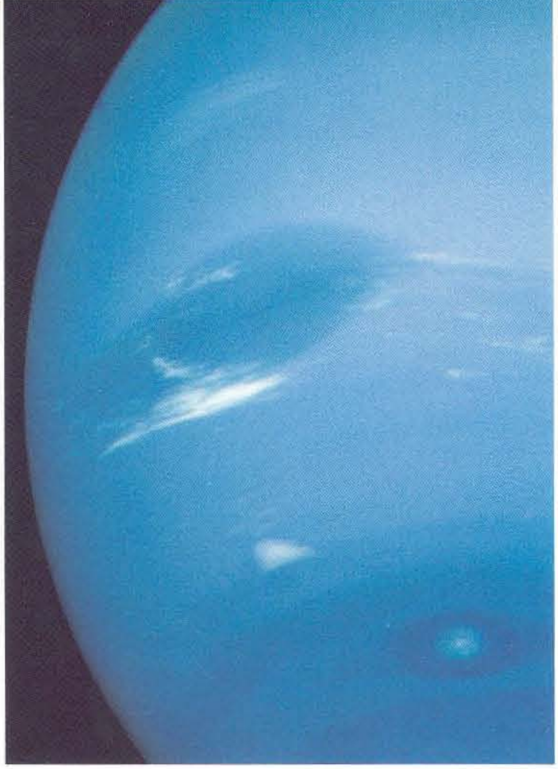
Why is the outer solar system so different from the inner? One of the reasons is that the outer planets formed at much greater distances from the Sun, where the whirling disk out of which they accumulated was much colder. Closer to the Sun where Earth formed, it was so hot that the only solids available to form planets were rocky materials. But five times farther out where Jupiter formed, the temperature was much lower, and water, which was in great abundance in the disk, was ice instead of vapor. So, the core of Jupiter accumulated out of cometlike objects containing both ice and rock. It was colder yet where Saturn formed, and the water ice could have also contained adsorbed ammonia, the form in which some of the nitrogen in the solar system was present. The water ice at Uranus, at −360° F, was cold enough to contain methane as well, which is one form in which the solar system's carbon existed at the time of planetary formation. Where Neptune formed, it was so cold (and still is) that methane itself was frozen solid and available to form giant planets.

Differences in the colors of the giant planets are a direct indication of the variation in composition of the icy materials that were accumulated to make the planetary interiors. Uranus and Neptune both look blue-green because methane is in greater abundance in those two planets; methane absorbs preferentially in the red end of the spectrum, making sunlight that is scattered back from the planet look blue-green. So even by eye we can see the importance of the temperature at which these giant planets formed.

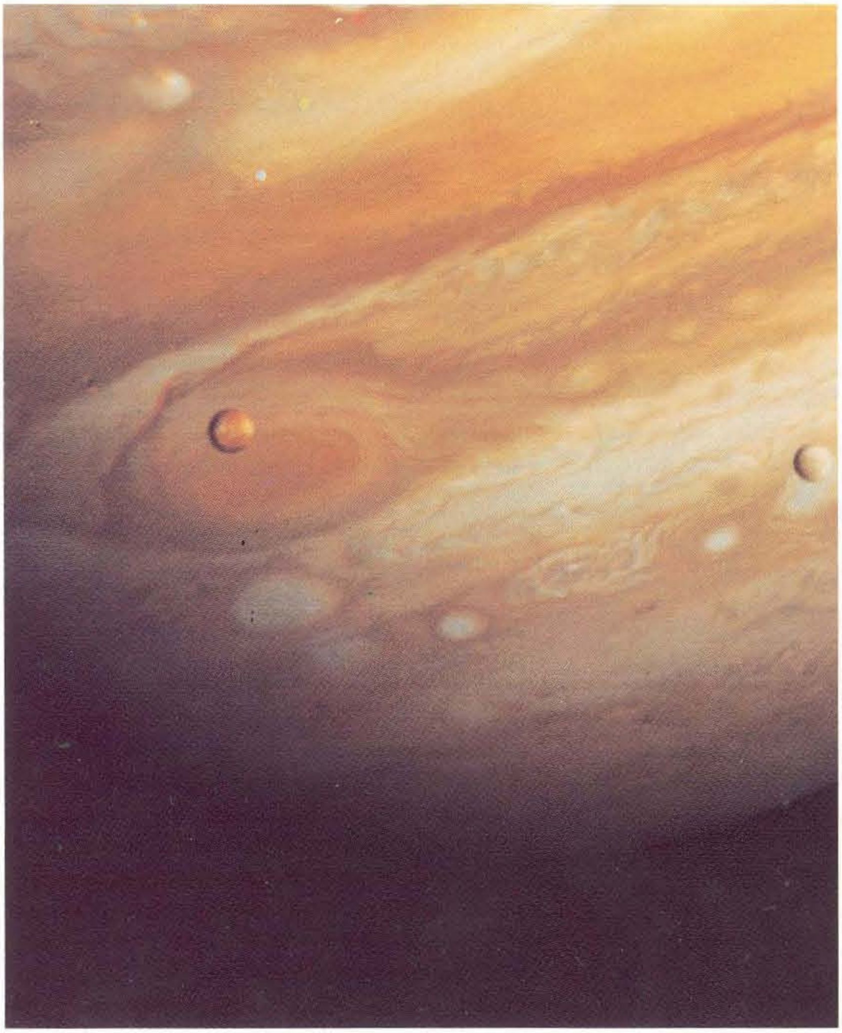
Atmosphere

What we see when we look at the giant planets is not a solid surface at all. Although the planet cores were formed out of icy and rocky objects, the heat generated by their collisional accumulation caused melting, leaving no solid surface inside these planets. Even the rocky material is melted, as it is in Earth's interior. The molten cores are buried beneath deep atmospheres of hydrogen and helium that also contain traces of water, ammonia, and methane. The interiors are very hot, but the atmosphere cools as it rises convectively, the temperature eventually dropping low enough so that water clouds form, just as water vapor rising in our own atmosphere forms water clouds. On Jupiter clouds of ammonium hydrosulfide form above the water clouds, and higher yet is the top cloud deck (the one we see in all the beautiful images of Jupiter) of ammonia ice crystals. On much colder Uranus and Neptune, the ammonia cloud deck forms deeper in the atmosphere and is difficult to see. Uranus and Neptune are both cold enough, however, that higher clouds of frozen methane can also form.

Such clouds provide an opportunity to study the weather systems in these giant rotating spheres of fluid and gas. One of the principal discoveries about Jupiter's atmosphere was that the Great Red Spot is a huge anticyclonic storm system rotating in a counterclockwise direction with a period of about six days and with winds of several hundred mph around its rim. And this was just the largest of dozens of such storm systems. Wind speed varies as a function of latitude, with a 200-mph eastward wind at the equator. With increasing latitude, westward and



Neptune's Great Dark Spot (right) is the size of Earth, and it's as large relative to Neptune as the Great Red Spot (below) is to Jupiter (shown here with its moons Io and Europa). Both are vast anticyclonic storm systems, but the higher winds on Neptune are carrying the Great Dark Spot around the planet at a speed of almost 700 mph. That storm system and the Small Dark Spot (lower right) are thought to be high pressure regions where methane is carried to a higher altitude.



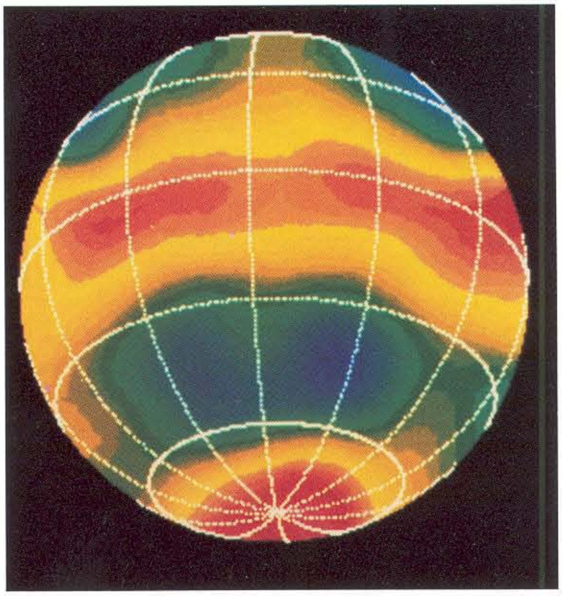
eastward jet streams alternate. Andrew Ingersoll, professor of planetary science, and former graduate student Timothy Dowling have shown that such wind shears generate small storm systems, which accumulate into larger storm systems.

Studying atmospheric dynamics on Uranus was more difficult because there aren't many visible clouds. Unlike Jupiter and Saturn, Uranus has a quiescent, stably stratified atmosphere. We think that this is partly because Uranus is radiating little more heat than it absorbs from the Sun. Jupiter, Saturn, and Neptune, on the other hand, radiate two to three times as much heat as they absorb from the Sun, indicating that their outer atmospheres are efficiently heated by an internal furnace or heat source. Uranus's atmosphere is not.

We didn't know exactly what to expect from Neptune's atmosphere. High-altitude hazes were detectable from Earth. A year ago, as Voyager 2 approached the planet, two images taken some hours apart first showed a bright cloud feature. Then, as the resolution of the images improved closer in, we discovered a Great Dark Spot, about one Earth in diameter—a hurricane-like storm as large relative to Neptune as the Great Red Spot is to Jupiter. We could also see a smaller dark spot with a white core, reminiscent of storms on Jupiter, and a small white cloud, which was named "Scooter" because it appeared to scurry so rapidly around the planet.

We believe that the high-altitude clouds next to the Great Dark Spot, which appear to have a wave-like pattern in them, are methane-ice clouds. They're perhaps similar to the clouds

Because sunlight is incident on Neptune's equator, the temperature is warmer there, as shown in this infrared map of brightness temperatures. But, surprisingly, the south pole is equally warm, while the midlatitudes are cooler, providing interesting clues to fluid flow inside Neptune.



So whether the Sun shines on the pole or on the equator, these two giant planets [Uranus and Neptune] somehow manage to have very similar temperature distributions.

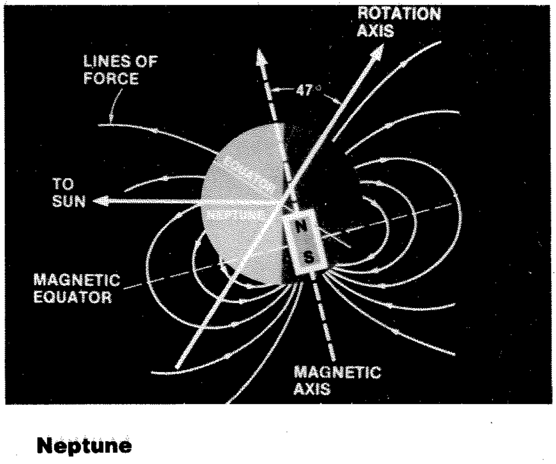
that form downwind of a mountain peak and remain attached to it. This suggests that the Great Dark Spot creates a high pressure region that forces the overlying atmosphere up to higher altitudes where it's colder. The central white cloud in the Small Dark Spot is also probably methane, suggesting that this is an upwelling region where methane is brought from deeper in the atmosphere up to an altitude where it freezes to form a cloud. We also observed some other white cirrus clouds, undoubtedly methane ice as well, which cast shadows on the deeper cloud bank 30–50 miles below. The deeper clouds are likely ammonia.

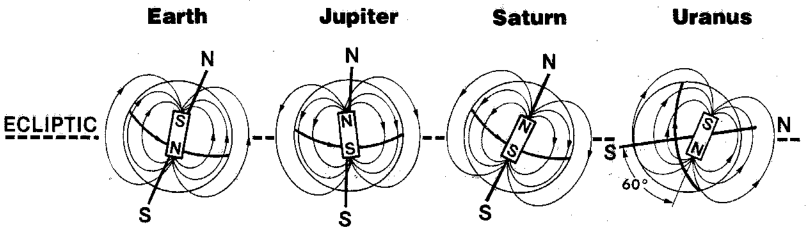
The temperatures of the two outer planets visited by Voyager are quite cold, although Neptune's temperature is about the same as that of Uranus because Neptune's internal heat source keeps it a bit warmer than it would be otherwise. Sunlight falls on Neptune's equatorial region, as on Earth, making the equatorial region warmer. But the pole is equally warm, while the mid-latitudes are colder. Although Uranus is tipped on its side with sunlight incident on its polar region, it has almost the same temperature pattern. So whether the Sun shines on the pole or on the equator, these two giant planets somehow manage to have very similar temperature distributions. This temperature pattern was a surprise, because we expected the incidence of sunlight to have some effect on the temperature. It is undoubtedly an important clue to the fluid flows inside the planets and to the means by which energy is carried from one region to the other, very important factors in understanding the weather systems on these giant planets.

We know from the magnetic field generated inside the planet that Neptune's interior is rotating with a period—that is, the length of its day—of 16.11 hours. Compared to that interior period, the Great Dark Spot is moving westward, opposite to the direction of planetary rotation, at a velocity that corresponds to a speed of almost 700 mph. Smaller clouds with twice this speed overtake the Great Dark Spot, making Neptune the windiest planet in the solar system—quite remarkable because the amount of energy available to drive the winds on Neptune is only 5 percent of the energy available on Jupiter. Yet somehow there are higher-velocity winds on this planet—an interesting puzzle for people like Andy Ingersoll and his colleagues. Although the winds have generated a great anticyclonic storm system, it's too soon to have any complete understanding of Neptune's Great Dark Spot, which looks just different enough from Jupiter's Great Red Spot to make it interesting.

Magnetic field

The interiors of Uranus and Neptune are somewhat similar—oceans of melted ice and rock, quite hot. (Jupiter and Saturn are mainly liquid hydrogen inside.) If fluid is heated from below, it will rise and convect, creating electrical currents because the water is electrically conducting. The electrical currents generate a magnetic field, which can be thought of in the simplest terms as similar to that of a bar magnet. The electrical current encircles the bar magnet, and





Earth, Jupiter, and Saturn have magnetic poles very close to their geographic poles, but the magnetic field of Uranus is tilted 60° from its axis of rotation. Although Uranus itself is tipped relative to the plane of the planets, Neptune is an upright planet like the other three. Its magnetic field, however, is also tilted 47°.

the magnetic field lines loop from one pole of the magnet to the other.

Here on Earth our magnetic pole is very near our geographic pole, which is very useful, because a compass points to the magnetic pole. That's also true of Jupiter and Saturn. Since Uranus was tipped on its side we expected its magnetic field to be similarly tipped. But one of the surprises of Uranus was that, unlike any other planet we had visited, its magnetic field was tilted 60° from the rotation axis of the planet. Also, the center of the magnetic field was not at the center of Uranus; it was offset by about three-tenths of the planet's radius. There were several explanations put forward as to why this might be the case. First, Uranus receives more solar heat in its polar regions, yet its equatorial region is equally warm. The atmospheric flow that carries the heat from the poles to the equator might also change the electrical currents deeper in the interior, so that they generate an offset, tilted magnetic field. A second suggestion is that we flew by Uranus just at the time that its magnetic field was reversing, as Earth's does every half million years or so. Although this is an unlikely occurrence, it can't be ruled out, and the debate was not resolved before we arrived at Neptune.

Neptune is not tipped on its side. We all expected that Neptune, being an upright planet (with sunlight on the equator, not the pole), would have an upright magnetic field. But we were surprised again: Neptune's magnetic field is tipped 47°. So it's difficult to argue that a tilted magnetic field comes from a planet's being tilted on its side, and it's even more unlikely that we flew by two planets just as their fields were reversing.

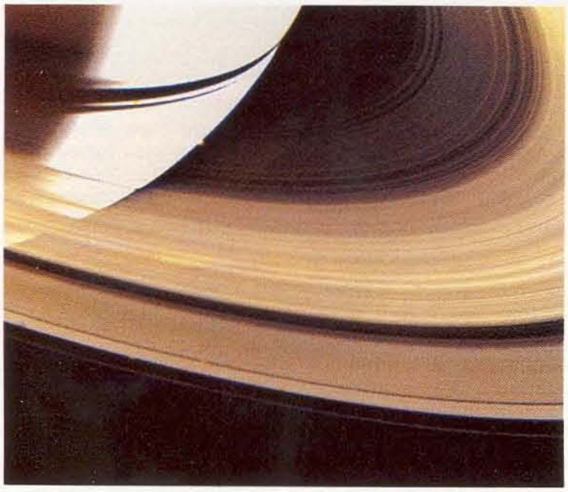
Because the tilted magnetic field rotates with Neptune, once every 16-hour day the magnetic field will be oriented so that the solar wind blows directly on the magnetic pole and compresses the field. (The solar wind is a tenuous, electrically charged gas, which blows at about a million mph outward from the Sun.) As Voyager approached Neptune we had our first observation of a pole-on magnetosphere. Of course, by the time Voyager flew over the top of the planet and down the other side, Neptune had rotated so that the magnetic equator, and not the magnetic pole, was facing into the solar wind, as is the case at the other planets.

The electrical currents that generate the magnetic field must be flowing fairly far out from the center of Neptune. The fact that both Uranus and Neptune have a similar tilt and offset to their magnetic fields is telling us something important about the nature of the flow of fluid inside these giant planets. It will likely take several years of study before we begin to understand the implications of these peculiar magnetic fields.

Rings

Saturn's rings are the quintessential ring system. Galileo discovered them in 1610, although he didn't really understand then that they were rings. Until 1977 they were the only known rings in the solar system. Voyager discovered a number of interesting features in Saturn's rings,

Voyager discovered many interesting features in Saturn's quintessential ring system (top), and Neptune's quite different rings (bottom) also provided some surprises. Neptune's ring arcs, first observed by star occultations from Earth, turned out not to be isolated segments but rather three brighter portions of a very thin, transparent, outer ring. Why ring material is confined to thicker arcs is still a mystery.



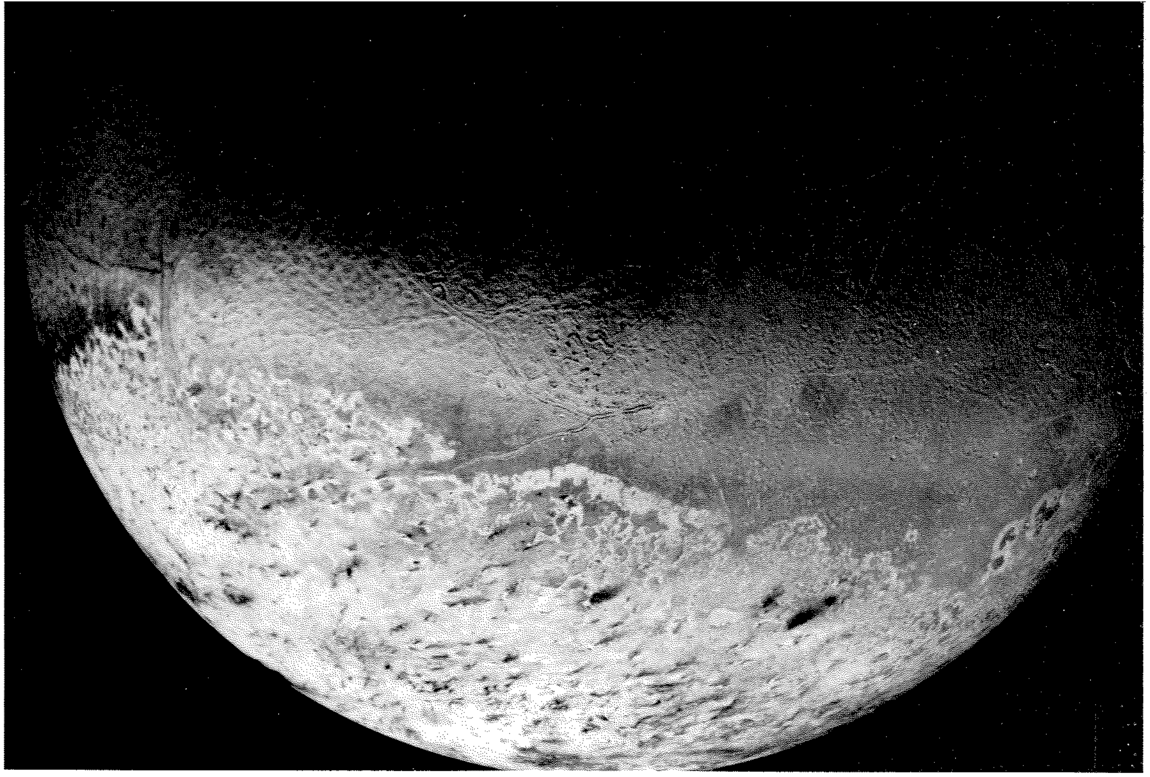
including waves that are generated by the gravitational pull of moons orbiting outside the ring. By looking carefully at these waves we have learned that the amount of water ice that makes up the particles in the rings would form a sheet about one to two feet thick if the particles could be collapsed into a solid layer.

Voyager also made an important discovery about the nature of Saturn's narrow F-ring, first observed by Pioneer 11 in 1979. Isolated narrow rings will not persist as narrow rings, because they're made up of countless numbers of particles that collide with each other, losing energy in the process. Some will spiral in to the planet and some will spiral away, causing the ring to dissipate rapidly. Peter Goldreich, the Lee A. DuBridge Professor of Astrophysics and Planetary Physics, and his colleague Scott Tremaine had earlier theorized that two shepherding satellites, one inside and one outside of a ring, would prevent it from spreading out and disappearing. As they predicted, Voyager found two moons flanking the F-ring.

From Earth we can't see rings around Neptune, but several astronomers, including Phil Nicholson (PhD '79) and his Caltech colleague Keith Matthews (BS '62), have searched for rings by observing stars as they disappear behind Neptune. About one time in ten, they found that the star would dim briefly as it passed behind material in orbit about the planet, as though there were pieces or segments of rings but not complete rings. Although we thought that there might be dozens of these ring arcs, Voyager found just three. Rather than isolated arcs, they're just somewhat brighter portions of a normal complete ring—the outermost, as it happens. The rest of the ring couldn't be seen from Earth because it's so transparent that you can see right through it. Only about 1 percent of the starlight coming through it is blocked, too small to be detected from Earth. There are a number of other rings, but they're also very thin.

The origin of the ring arcs is still a puzzle. The question is: Why do we see material concentrated in arc regions? We don't know whether the arcs are due to objects embedded in the ring at that location or to other unseen moons. We have found two moons that may shepherd the inner edges of rings, but they can't account for the ring arc regions.

We think the rings are probably the result of collisions. One of the key questions before Voyager's journey to the outer solar system was: Are rings primordial? That is, are they just material left over from when the planet and the moons formed? Or are they a more recent addi-



Triton may have hit one of Neptune's regular moons, lost enough energy so it could no longer escape, and remained in an elongated, retrograde orbit.

tion to the planet—the result, perhaps, of a catastrophe in which a moon was struck by a comet and broken up into pieces? Two larger pieces might have captured and herded some of the smaller residue of the catastrophe between them. I think that the Voyager observations are telling us that it is likely that rings are not primordial, but are the result of catastrophic processes.

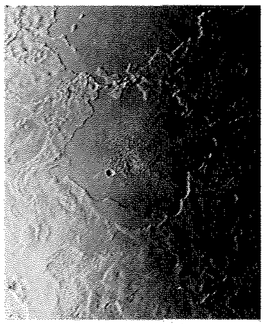
There is other evidence for catastrophic collisions. Voyager discovered six dim moons at Neptune. The outermost of these new moons is only 250 miles across, is rather irregularly shaped, and is marked by a huge impact crater. If the object that made that crater had been much larger, 1989N1 would have been shattered. Several of the smaller moons closer to the rings likely resulted from such a breakup of a larger object.

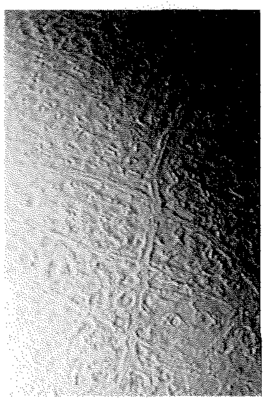
Triton

One large moon also orbits Neptune. Triton was first seen shortly after Neptune was discovered. It's remarkable how much was already known even though the moon is just a point of light when viewed from Earth. We knew that there was methane ice and possibly solid nitrogen on its surface. We knew that it orbited backwards around the planet. No other large moon orbits backwards; they all orbit in the same direction as the planet rotates because they share the rotation of the disk of gas out of which they formed. As the bodies form, they continue orbiting in that same direction. This motion, called prograde motion, is characteristic of regular satellites that form as a part of the planetary formation process itself. So how do we explain an object orbiting in the opposite way, in a retrograde orbit? It is likely that many such objects formed elsewhere in the outer solar system and were accreted by Uranus and Neptune as *they* formed. But two of them escaped that fate and survive as Pluto, which orbits the Sun, and Triton, which came close to Neptune, but not so close that it was swallowed up. Triton may have hit one of Neptune's regular moons, lost enough energy so it could no longer escape, and remained in an elongated, retrograde orbit.

But a moon in an elongated orbit has a serious problem. All the normal satellites like our own Moon have one side facing the planet. Just as the Moon raises a tide in our oceans, the Earth raises a tide in the Moon's surface, causing a permanent deformation since it always faces one way. This isn't possible in an eccentric orbit because the moon can't rotate at exactly the right rate to keep one face in. As different sides of the moon face the planet, its surface will heave up and down like the surface of our oceans. The flexing of the moon's crust generates heat that melts its interior. This energy dissipation continues until the orbit becomes circular and one side of the moon always faces the planet.

According to Peter Goldreich and his Caltech colleagues Norman Murray, Pierre Longaretti, and Donald Banfield, this is probably what happened to Triton. They calculated that Triton would have been melted by tidal pumping of its surface for about a billion years before its orbit finally became circular as it is today. We were





Triton's icy south polar cap (left) exhibits features such as the "cantaloupe terrain" toward the equator, unlike anything yet seen in the solar system. Evidence of thermal activity appears in an active geyser (lefthand arrow in stereo image at right) with a plume 5 miles high and more than 100 miles long (right arrow); in volcanic craters (below) that have undergone episodic melting and freezing; and in fault lines extruding viscous water ice (bottom).

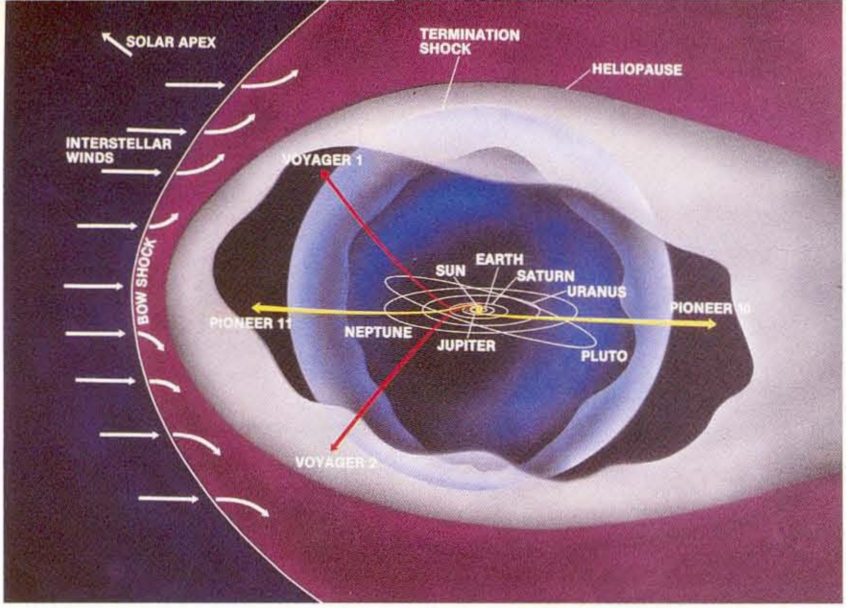
expecting that there had been an era of violent geologic activity in Triton's past resulting from its capture and orbital evolution around Neptune.

We also thought that Triton would have a seasonal polar cap of methane ice and possibly nitrogen ice. The seasons don't change quickly on Triton—its year is 165 Earth years long. When it's summer in the southern hemisphere, that polar cap will sublimate, creating a tenuous atmosphere that will flow to the dark, cold north polar region, where it will freeze out to form a new polar cap. When summer comes to the north, that polar cap will then sublimate and freeze out again on the southern pole. This idea was first proposed some years ago by Robert Leighton, the William L. Valentine Professor of Physics, Emeritus, and Professor of Planetary Science Bruce Murray to explain Mars's polar cap, which migrates in a similar fashion although it's made of carbon dioxide ice. Evaporation of the carbon dioxide from one polar cap changes the atmospheric pressure on the surface of Mars by a factor of two as the seasons wax and wane and the polar cap freezes and sublimates. Although it's much colder on Triton (−390° F) than on Mars (−200° F), Laurence Trafton (BS '60) suggested that a similar phenomenon involving methane polar caps should be occurring on Triton.

So what *did* we see on Triton? As we approached we managed to resolve the icy polar cap of the south pole and realized that our view of the surface wouldn't be obscured by a hazy atmosphere; we would indeed be able to see it in fine detail. The south polar cap probably consists of a layer of nitrogen ice and methane ice on top of a surface that is primarily water ice. At −390° F, water ice is rock hard. There is also evidence of geologic activity—long fault lines out of which viscous water ice has been extruded, forming parallel ridges. The chaotic-looking area closer to the equator has been dubbed the "cantaloupe terrain." It's unlike anything we've seen before, and we're still trying to understand what geologic processes could have created such a surface. In a nearby region there is very smooth terrain with features that look like the volcanic calderas or craters that we have on Earth. But instead of Earth's rocky crust and crater floors covered by the flow of molten rock, Triton has an icy crust and crater floors covered by water flows. The sharp detail of an impact crater about 10 miles across tells us that this material is quite hard and must therefore be water ice. If it were methane or nitrogen ice we would not see such sharp features, because even at −390° F those ices are soft and flow like glaciers flow on Earth.

If we look more closely at that caldera we see evidence of several episodes of icy flow. This icy volcanism may have occurred about a billion years ago or even more recently, perhaps the result of a combination of radioactive and tidal heating. There is no tidal heating source today, only radioactive and solar heating.

There is, however, contemporary thermal activity. In the icy polar cap there are many parallel dark streaks, which seem to emanate from points and fan out in a characteristic shape



The two Voyager spacecraft (as well as Pioneers 10 and 11) are now headed for the heliopause, which signals the actual end of the solar system. The termination shock occurs where the solar wind slows down dramatically before meeting the interstellar wind.

as though carried by a wind. In stereo views of two regions, Laurence Soderblom (PhD '70) and his colleagues found geysers with vertical streams five miles high and long plumes of material whose shadow we can see below on the surface. The shape of the plumes indicates that Triton has a stable atmospheric layer about five miles thick; above that is a strong wind shear, which carries the erupted material off in a long stream, just as smoke is wafted away from the top of a chimney.

How can there be active geysers where the surface temperature is −390° F, the coldest surface we've seen in the solar system? At that temperature nitrogen is solid and there's a little bit of vapor associated with it. But nitrogen is not much below its melting point, so a little heat will increase its vapor pressure enough to force the nitrogen out into a plume. In this sense nitrogen is behaving much like water behaves on Earth; beneath Old Faithful water is heated enough to cause it to erupt explosively from the vent.

We're not at the end of our mission of exploration.

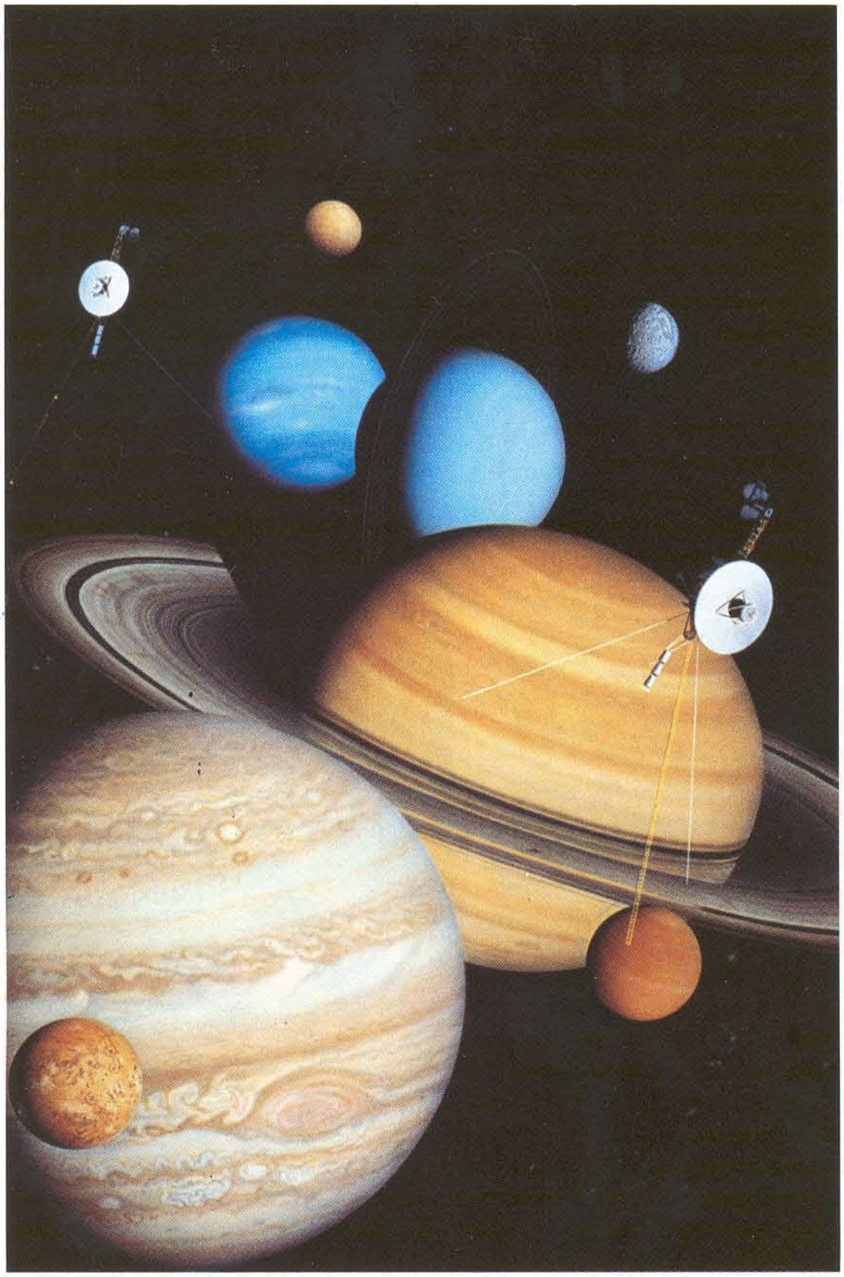
In many ways Triton is a twin of Pluto and may be providing our best look at that remote planet for many years to come. They are almost the same size; they both have methane on their surfaces; their densities are about the same—about twice that of water, which means that they are three-quarters rock and one-quarter water ice coated with methane ice. But Pluto's evolution, and thus its surface, will almost surely be quite different from Triton's, because Pluto would not have been subjected to tidal heating as Triton was in its orbit around Neptune.

Beyond Neptune

We're not at the end of our mission of exploration. The space between the stars is filled with a tenuous gas and our Sun, like all stars, is blowing a bubble in that interstellar medium. The bubble, which is called the heliosphere, is created by a million-mph wind blowing radially outward from the Sun in all directions. We don't know how far it is to the heliopause, the edge of the bubble; it may be three to four times as far as it is to Neptune, that is, 90–120 times as far from the Sun as Earth is. Before the solar wind reaches the heliopause there will probably be a supersonic shock, because the supersonic solar wind must slow down before it finally runs into the interstellar medium. We hope Voyager will tell us where these boundaries of our solar system are. This may be a unique opportunity, because in the next phase of exploration, spacecraft will go into orbit around a planet rather than escape the solar system. If nothing unfortunate happens to the two Voyager spacecraft, we can track them for another 25 years—at which point Voyager 1 will be 130 times as far from the Sun as Earth, and could be in interstellar space for the first time.

The next phase of exploration of the outer planets has already begun. Galileo was launched last October for a return to Jupiter. It will put a probe into Jupiter's atmosphere, directly measuring the winds, the temperatures, and the composition of the gas and the cloud layers. And the spacecraft will go into orbit around the planet so that we can study it over several years rather than just take snapshots as we fly by. Galileo

An all-inclusive retrospective of Voyager's journey, collapsed into one painting by artistic license, shows Jupiter and Io, Saturn and Titan, Uranus and Miranda, and Neptune and Triton.



will fly 100 times closer to Jupiter's moons than Voyager and will reveal their surfaces in much more detail. In 1996 the Cassini mission will be launched on a return to Saturn and will place a probe into Titan's atmosphere—an atmosphere that is primarily nitrogen like that here on Earth, but that has an organic chemistry that may be similar to that present in Earth's atmosphere before life evolved. Again, the spacecraft will go into orbit, allowing detailed studies of the dynamics of Saturn's ring system. In 1995 the Comet Rendezvous Asteroid Flyby (CRAF) mission will send a similar spacecraft to a comet. We believe that the cores of the giant planets are accumulations of comets that formed in the outer solar system. CRAF will measure the properties of a comet by penetrating its dark, icy crust with an instrumented probe.

Although these new missions and others to follow will add important chapters to the encyclopedia of the outer solar system, the chapters written by the two Voyager spacecraft over the last 12 years will not be forgotten, because they first revealed to us a solar system with distinctive worlds of unexpected richness and diversity. □

As project scientist of the Voyager mission since 1972, Ed Stone has coordinated a large team of scientists in analyzing the images and data that the two spacecraft sent back along their journeys —and he's communicated the excitement of Voyager's scientific discoveries to an audience of millions around the world. Stone joined the Caltech faculty after receiving his PhD in physics from the University of Chicago in 1964. He has been professor of physics at Caltech since 1976, chairman of the Division of Physics, Mathematics and Astronomy from 1983 to 1988, and is currently vice president for astronomical facilities. His own area of research is cosmic rays, and although the Voyager spacecraft have left the planets behind, Stone's work has just begun; an abundance of cosmic rays is waiting out there around the termination shock. Stay tuned for another 10 years or so.