EIR Feature

Voyager reveals the mysterious planet Neptune

by Marsha Freeman

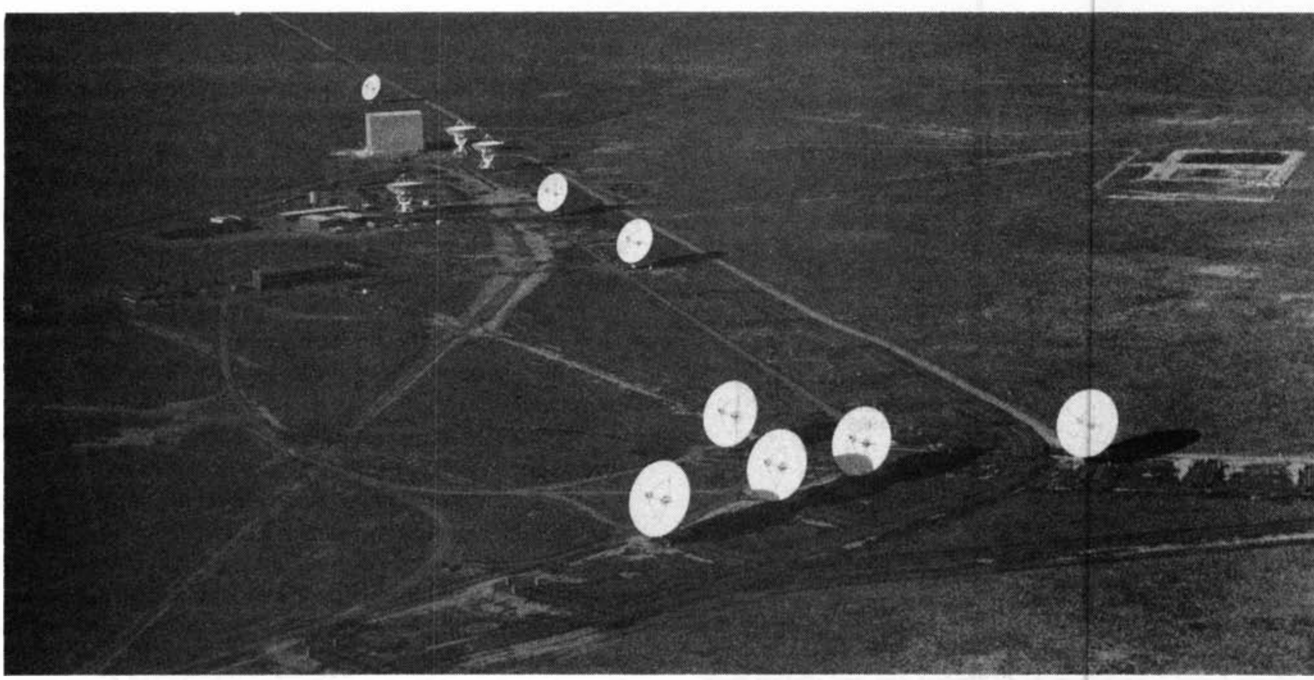
The massive amount of data that Voyager 2 has returned from its visit to Neptune will keep scientists busy for years. Some of the data collected by Voyager which was stored on the spacecraft's tape recorder and later played back to Earth, has not even arrived yet from the tracking stations where it was received, to the scientists. This report, therefore, can only be preliminary, as much more will be learned soon about Neptune's weather, rings and satellites, magnetosphere, and its intriguing moon, Triton.

Because Neptune is so far from the Sun—nearly 3 billion miles—it receives nearly 1,000 times less sunlight than Earth. At Neptune our Sun would look like just a spot of light in the sky. On the Earth and other planets, energy from the Sun helps drive weather systems, so the fact that Neptune receives so little energy from the Sun, led scientists to expect a planet considerably more bland than Jupiter or Saturn.

Observations from Earth had indicated that there might be thin ring arcs around Neptune, because although parts of rings were observed on one side of the planet, the same rings were not observed on the other side. Voyager found that there are three complete rings around Neptune, although one is particularly clumpy in spots, and that there is also a thin sheet of ring-like particles.

From Earth, astronomers knew that Triton has an atmosphere—only the second moon, after Saturn's Titan, to hold such a claim. But virtually nothing about the surface of Triton was known. Voyager has revealed a body that looks hauntingly like Mars. It appears that at one time Triton had flowing liquids, active nitrogen volcanoes, and "oceanic" floods. It is quite possible Triton is geologically active today, and that its weather and climate still change dramatically with its changes of season.

How are such dramatic, rapidly changing weather systems and storms produced on a such a cold planet? Why does Neptune have a magnetic field which is entirely different from any of the other planets, and what effect does this have on



The 27 eight-foot-diameter antenna dishes of the National Radio Astronomy Observatory's Very Large Array Radiotelescope at Socorro, New Mexico, were pressed into service along with the Deep Space Network antennas in Spain, Australia, and California, to capture the volumes of data that Voyager 2 sent back from Neptune.

its rings, moons, and atmosphere? How do Neptune's tenuous rings "hold together," and how quickly are these rings changing?

Why does Triton orbit Neptune in a retrograde direction (opposite from the direction of rotation of the planet), and what does that mean about its past? Did the moon have water which flowed on the surface, smoothing over the older craters? Are there volcanoes on Triton that are still actively spewing out nitrogen into its atmosphere? How does Triton's atmosphere interact with Neptune's magnetosphere?

Some answers, many questions

Scientists will be able to coax answers to some of these questions from the data Voyager has sent us from Neptune over the next months and years, while other questions may have to go unanswered for the time being.

It is beyond the capability of today's propulsion technology to allow us to return to Neptune in a reasonable amount of time by going there directly. Voyager 2's Uranus and Neptune fly-bys were possible because there was a planetary alignment that happens only once about every 176 years. By using first Jupiter, and then Saturn, to get an added boost or gravity assist, the spacecraft was able to make it to Uranus and Neptune in good time, without carrying tons of fuel (see **Figure 1**).

Voyager 2, which was only "tasked" to go as far as Saturn, has given us the best look we will get of Uranus and Neptune for a long time.

Not only is Neptune a marvel, but equally so is the Voyager 2 spacecraft itself. Celebrating the 12th anniversary of its launch just four days before it had its closest encounter with Neptune, the amazing one-ton craft performed flawlessly. What Voyager had to contend with in order to successfully send back spectacular images of Neptune and Triton pays tribute to the dedicated engineers who kept in touch with it, patiently fed it updated computer commands, constantly monitored the health of the craft and all of its scientific instruments, and figured out how to obtain the highest science return, even in the face of hardware glitches (**Figure 2**). The spacecraft was pushed to, but not beyond, the limit of its capability.

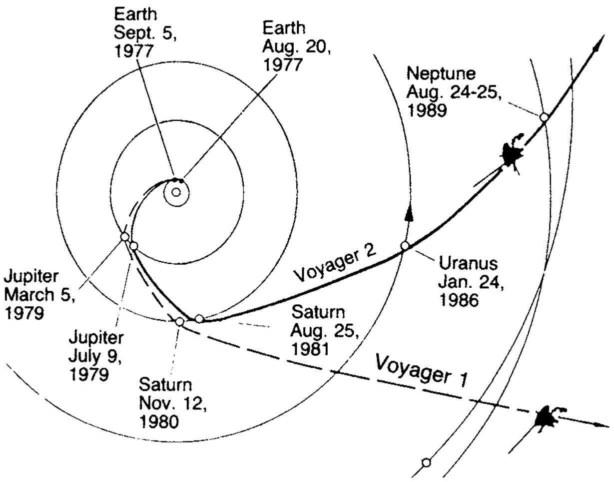
Although the distance between Neptune and Earth is "only" 2.8 billion miles, Voyager's journey did not go as the crow flies. Due to its swings around the other giant planets, the spacecraft had traveled about 4.4 billion miles when it arrived near Neptune last month. Though the spacecraft was "arthritic and hard of hearing," specialists on the ground found ways to overcome the problems and maximize the data return. As a number of scientists commented, because of changes made on the ground, Voyager 2 was a more capable spacecraft *after* 12 years of operation, than when it was launched.

Solving problems from 3 billion miles

During the long and lonely years that Voyager traveled between planets, it was in a cruise mode. But during a pla-

FIGURE 1

Trajectories of Voyager 1 and 2



Voyagers 1 and 2 were launched 12 years ago and sent on their grand tour of the Solar System, accelerated by gravity assists at each planet. Voyager 1 made its last encounter in 1980 at Saturn, and Voyager 2 is now also cruising through interplanetary space.

netary encounter, where the most important data would be gathered in a matter of hours, the spacecraft had to do many things at the same time. Two problems on the craft added to the inherent difficulty.

On April 6, 1978, Voyager's computer software switched the spacecraft from its primary radio receiver to the backup. This was less than a year after launch, and more than a year before its first stop, Jupiter. After a command was sent to return to the primary receiver, it failed. Seven days later it switched back to the backup.

This is no small failure, because the receiver is the instrument that allows the spacecraft to receive communications from Earth. The backup receiver, it turned out, had a faulty tracking loop capacitor, which meant that the receiver could not lock onto a variable transmission frequency. As a result, the ground transmitter had to send its commands to Voyager at a very precise frequency in order to be heard. But as the spacecraft changed speed relative to the Earth, the frequency of the signal it would "hear" would also change, because of a phenomenon known as a Doppler shift. The Doppler shift is similar to the change in pitch you hear from a train whistle when it is far away, as opposed to when it is passing in front of you, and changes again as it recedes into the distance.

Communicating with a spacecraft which is "tone deaf" is quite complicated. It means exacting calculations must be made to determine how the transmitted frequency would change with changes in Voyager's speed, which takes place in relation to the tracking station antennas as the Earth rotates. The signal must then be adjusted so it arrives at the frequency Voyager can "hear." This means that the three Deep Space Network antennas which communicate with Voyager must constantly vary the frequency at which they are sending. Also, the frequency at which Voyager received would change when the receiver warmed up, which happened whenever the spacecraft had been active for a while. An unpredicated change of as little as *one-quarter of a degree centigrade* would cause the frequency to shift enough for Voyager to "turn a deaf ear." Engineers at the Jet Propulsion Laboratory learned to allow the spacecraft's receiver to "cool down" before sending commands.

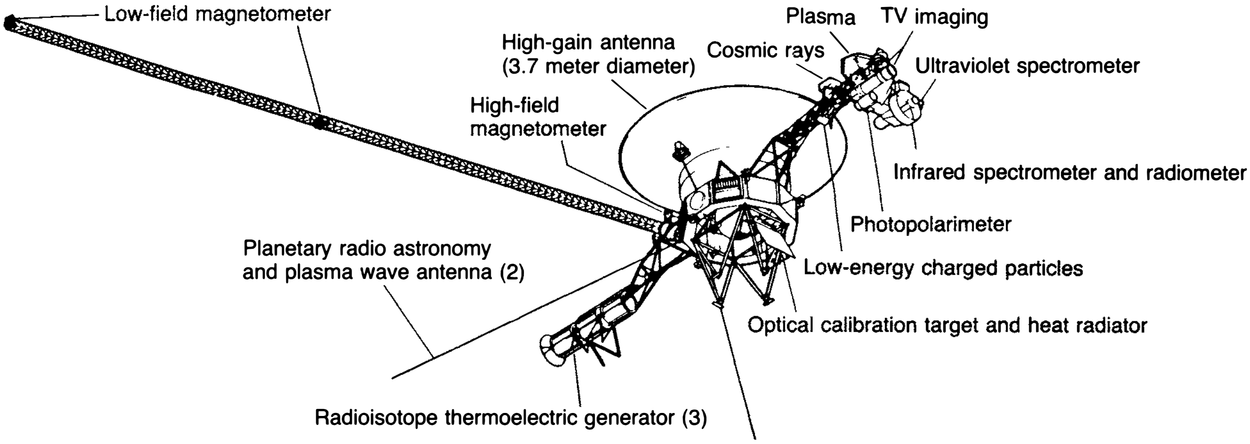
The only other major problem enountered by the intrepid spacecraft was a harrowing jam in one axis of its scan platform just after its 1981 encounter with Saturn. The platform supports the scientific instruments on Voyager that require precise pointing, which include the cameras of the imaging system, the ultraviolet spectrometer, the infrared interferometer, and the photopolarimeter system. If the platform had remained immobile, it would have been very difficult for Voyager to point its instruments precisely at its planetary targets, no matter how many computer commands were sent. Two days after the platform stuck, it was movable again. Three years of analysis and testing showed that the problem was a loss of lubricant at high speed. The scan platform has only been moved at a slower speed since then.

Engineering wizardry has kept the Earth in touch with Voyager, and its instruments precisely pointed. But being close to 3 billion miles away produces its own difficulties.

Did you ever take a picture out of the window of a speeding automobile? If you are aiming at a mountain in the distance, and can hold the camera steady, you will get an acceptable photograph. But if you are going 60 miles an hour and try to photograph a house on the side of the road, the image will be smeared. You might try using very fast film, and leaving the camera shutter open for a small fraction of a second. But at Neptune, the speeding Voyager spacecraft was taking pictures of nearby objects, which are not brightly lit, but are as black as coal, like the rings of Neptune and its small moons. Because of Neptune's great distance from the Sun, and small amount of light that falls on these black objects, the camera shutters had to be left open *longer* than at the other planets in order to capture the details.

Since longer exposure times under these conditions would result in blurred pictures, space scientists had to develop image-motion compensation techniques. "Classical image-motion compensation," used during the Uranus encounter, involved rotating the entire spacecraft to track the target during the exposure. Continuing our analogy, this would be as if the camera on our speeding car were mounted on the trunk and could swivel to track the passing house on the roadway. However, turning the craft in this way moved it out of contact with Earth, and its images had to be stored onboard

FIGURE 2
Voyager spacecraft



The Voyager spacecraft is outfitted with 11 science experiment systems, which include searching for particles and magnetic fields, as well as observing objects in various wavelengths of light. The high-gain antenna is the spacecraft's communication link with Earth.

for later transmission.

A similar maneuver, which preserves the real-time transmission of images, is the "nodding" image-motion compensation technique where the spacecraft is only rotated to a point that it does not lose contact with Earth. The spacecraft then rolls back to its original position, or "nods." "Maneuverless" image-motion compensation uses only the movable scan platform to track the target, while the spacecraft's entire orientation to Earth remains static. All of the work that went into developing and implementing these techniques paid off in the clarity and detail we now have in the photographs of Neptune and Triton.

The ability to receive data on Earth was also a challenge to Voyager's team. With Neptune nearly six times the Earth-to-Jupiter distance, the maximum data rate that can be received at Earth and still be able to be "heard" above the background noise would naturally fall by a factor of nearly 36, because the signal strength is the inverse of the square of the distance. At Jupiter, the Deep Space Network antennas could reliably receive 115.2 kilobits per second (kbps); 44.8 kbps at Saturn; and 29.9 kbps at Uranus. At Neptune, the Voyager team was able to preserve a data return rate of 21.6 kbps, despite the increase in distance.

The three large 210-foot-diameter radio antennas in the Deep Space Network stations in Spain, Australia, and California, were torn up and enlarged to 224 feet, which improved the signal strength by 55%. In addition to these three facilities, the Australian Parkes radio astronomy 210-foot diameter antenna, the 210-foot antenna at Usuda in Japan, and the 27 eighty-foot-diameter antenna dishes from the National Radio Astronomy Observatory's Very Large Array antennas in New Mexico were added to the network.

By simultaneously tracking Voyager from all of these antennas, a significant increase in combined signal strength was achieved, roughly proportional to the combined surface areas of all of the antennas. To make the most of each of these precious few bits of data Voyager can send back, engineers also figured out ways to reduce the number of bits of data needed to transmit images.

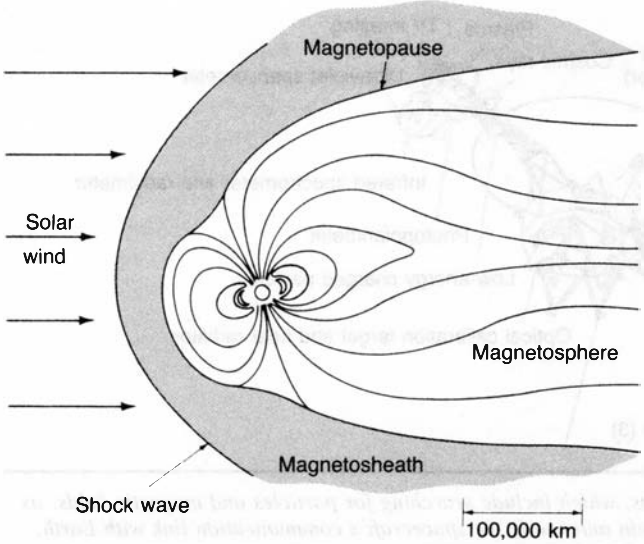
One way of reducing the volume of data that Voyager had to transmit, for example, to send an image, was to compress the data. To do this, each line was divided into blocks of five pixels, or picture elements. The pixels sent are actually in 255 shades of gray. The absolute brightness of the first one in each line is sent, but the brightness of each following pixel is expressed as the difference in brightness from the preceding one.

With all of these years of readying the spacecraft for its encounter with Neptune, the scientists were much more prepared for the performance they could expect from Voyager than what they were expecting to find on Neptune.

Neptune's changeable dark spot

Voyager started seeing things in the Neptunian system that observers could not see from Earth, months before it arrived close to the planet. Striking weather and atmospheric features, such as the great dark spot, were photographed for 60 days before its close approach on Aug. 24, and the photos were compared to see if "weather predictions" could be made from millions of miles away. On July 7, when Voyager was still 43 million miles from Neptune, NASA announced that a new moon had been discovered two days earlier. An Aug.

FIGURE 3
The Earth's magnetosphere



The relatively simple magnetosphere around the Earth shows the major components of the effects of the Earth's magnetic field. The bow shock is formed when the solar wind, flowing at a million miles per hour, hits the magnetic environment of the planet, slowing to subsonic speeds. At Neptune, however, the magnetic field lines are not symmetric with the rotational exis of the planet, and would appear in a similar diagram to come out of the equator.

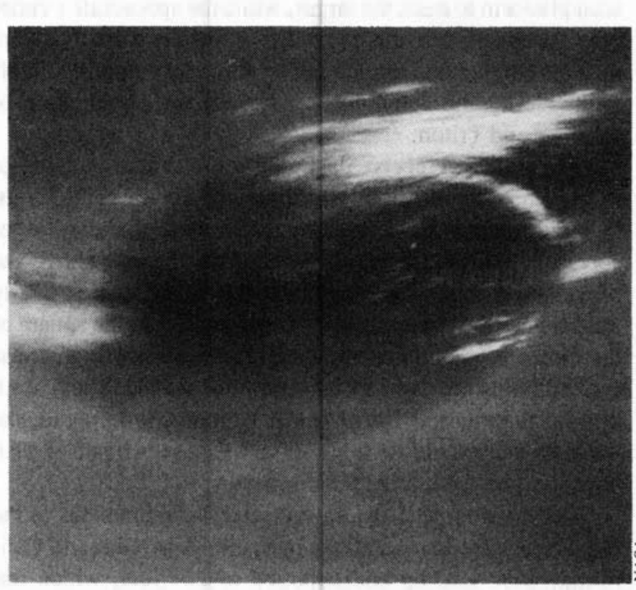
3 announcement brought the total of new moons discovered to four, as three more showed up in photographs, taken 22 million miles from Neptune. These discoveries led scientists to believe that when Voyager got up close, many more small moons would be found, although only two more were found.

Two weeks later, planetary radio science experiment investigator James Warwick of Radiophysics Inc. announced that radio emissions from Neptune had been confirmed, which indicated that the planet has a magnetic field, and that other phenomena related to a magnetic field, such as aurora and radiation-darkened rings and moons, would likely be found. The radio emissions are generated by high-velocity charged particles as they spiral along magnetic field lines into the planet's atmosphere. Analysis at that early date estimated Neptune's magnetic field to be similar in strength to those of the Earth and Uranus.

On Aug. 21, daily press briefings began at JPL, which continued until Aug. 29. At the first briefing, Warwick reported that Neptune's radio emissions had a 16-hour period, which would be most simply explained as being the rotation period of the planet's interior. Until that time, the best estimate of the rotation period, or length of day, on Neptune was nearly an hour longer.

Imaging team leader Bradford Smith from the University of Arizona reported that Voyager photographs showed a dynamic, constantly changing atmosphere with large and small dark spots. "Neptune is an extremely dynamic planet," Smith said, "with less than 50% of Jupiter's energy." The white, cirrus-like clouds were spotted, and it was proposed that they were at extremely high altitudes. The same day, Voyager 2 performed its final trajectory-correction maneuver, which nudged it slightly to the right, and increased its velocity by 1.1 miles per hour, which placed the spacecraft 91 miles farther from Neptune, but 439 miles closer to Triton.

One of the first direct measurements scientists expected to receive from Voyager days before the closest approach was evidence that the spacecraft had crossed the bow shock created when its own magnetic field slammed into the constantly flowing solar wind (see **Figure 3**). Not knowing quite what to expect, project scientist Edward Stone, from the California Institute of Technology, remarked that Voyager crossed Jupiter's bow shock at 99 Jupiter radii, or over 4 million miles' distance from the planet. So the scientists waited. On Aug. 22, seeing no evidence yet of the bow shock crossing, Stone proposed that it may be only a half-million miles from Neptune. At that distance, the corresponding field strength would be about what it is at Earth's equator, he thought, or 0.3 gauss. Three days later, Donald Gurnett of the University of Iowa, announced that Voyager *had* crossed the bow shock earlier that morning, which was evident from the turbulence measured by the plasma wave instrument. Norman Ness, of the Bartol Research Institute, added that



Voyager took this close-up of Neptune's great dark spot at a distance of 1.7 million miles. The spiral structure of both the dark boundary and the white cirrus clouds suggests an anti-cyclonic storm system rotating counterclockwise in the southern hemisphere. Periodic small-scale patterns in the white clouds, which might be waves, are short-lived.

the planetary radio astronomy experiment located the bow shock crossing at 35 Neptune radii, or about 525,000 miles.

Scientists now knew that the last giant planet has a relatively weak magnetic field, but they were hardly prepared for what was to come. On Aug. 26, John Belcher from the Massachusetts Institute of Technology said that the scientists had assumed that, like the other planets, Neptune would have a bipolar magnetic field, more or less aligned with the axis of rotation of the planet. On Earth, for example, magnetic North is relatively near the North Pole of the rotational axis. But Belcher revealed that as Voyager approached Neptune from the south, and then came up to go over its north pole, the instrument revealed that the magnetic equator is off by *three hours* from the rotational equator. He explained that this indicated that the magnetic pole is inclined at least 30 degrees from the rotational pole.

It was no wonder then, that Voyager did not find any aurora when it went over the north pole of Neptune. At Earth's poles, the plasma from the solar wind is able to enter into the atmosphere, since the magnetic field is very weak there. These spiraling in particles produce the atmospheric glow, the Aurora Borealis, or the Northern Lights, in the Northern Hemisphere. But at Neptune, the weak part of the magnetic field, or pole, is at the planet's equator, and it is there that any aurora would be found. The scientists are still carefully analyzing the Voyager data to see if they can find aurora where they were not looking before. The day after this astonishing announcement, Ness said that Neptune's field is probably multipolar, inclined 50 degrees to the rotational axis, and that its polarity is the opposite of Earth's.

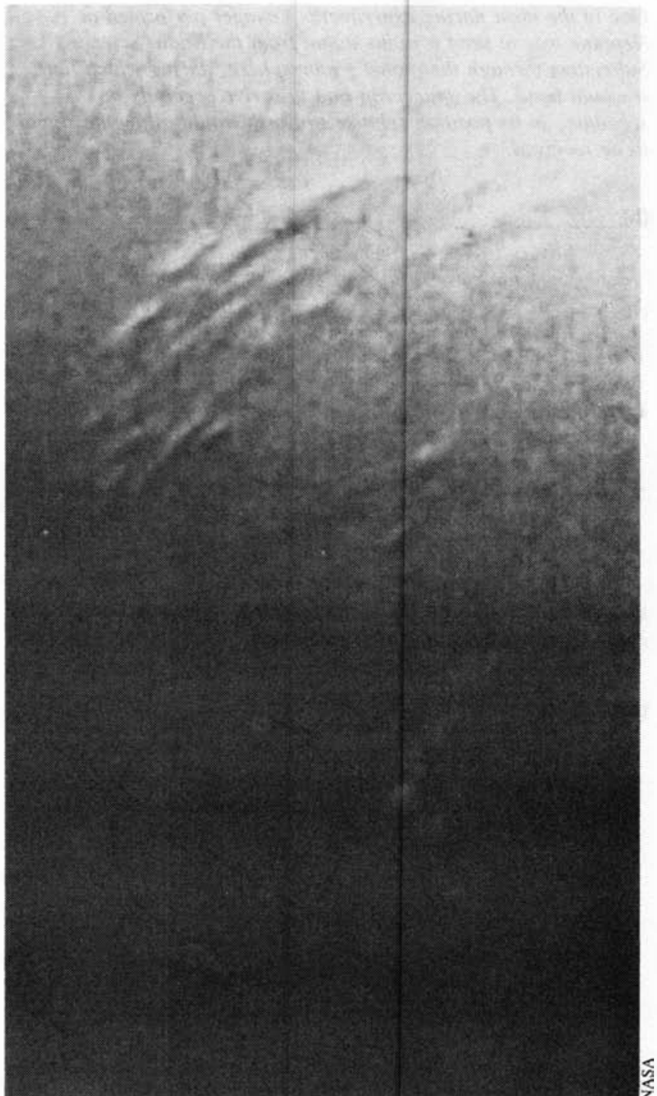
Voyager did find that Neptune has belts of radiation, like the Earth's Van Allen Belts. This is a high-temperature (1 biilion degrees), low-density plasma region, which can cause radiation damage to the rings around the planet, and which may account some for their dark color.

At the last briefing the following day, Donald Gurnett reported that in the inner magnetosphere of Neptune, the plasma wave instrument detected "whistler mode waves." These waves, which actually sound like a whistle, can be caused by electrons spiraling along magnetic field lines in the radiation belts. They can emit whistler mode waves when interacting with radio waves in the plasma, which change in frequency (pitch) as they oscillate. Gurnett mentioned that this phenomenon takes place in magnetic fusion experiments, where there is a loss of electrons, and energy, in the magnetically confined plasma.

Norm Ness reported at the science wrap-up briefing that not only is Neptune's magnetic field inclined 50 degrees, it is offset four-tenths of a Neptune radius, or about 6,000 miles, from the center of the planet. Because of their high inclination, the moons "slosh around" in the magnetosphere, which changes as the planet rotates. It will take quite some time before scientists have a more detailed understanding of this most unusual magnetic field structure.

What's the weather on Neptune?

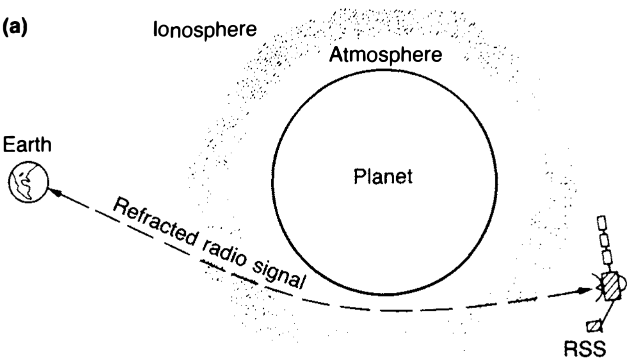
If you think predicting the weather on Earth is difficult, try Neptune. Even from millions of miles away, Voyager's cameras showed scientists that the great dark spot on Neptune was changing, and they correctly assumed that this feature is a large atmospheric storm system, similar to Jupiter's red spot. In order to predict the weather, both information and photographs are necessary. Voyager has a number of scientific instruments that are used to "look" at the atmosphere, to "see" the winds, particles, chemical composition, and clouds. **Figures 4a-c** depict drawings of three of these instruments. By "viewing" Neptune at wavelengths of light, such as the infrared or ultraviolet, that neither the eye nor the imaging



At Neptune, Voyager was able to photograph the shadow the white clouds cast on the lower methane cloud deck, for the first time at any planetary encounter. The smallest cloud feature is 28 miles in diameter. This photo was taken on Aug. 23, one day before the closest encounter with Neptune.

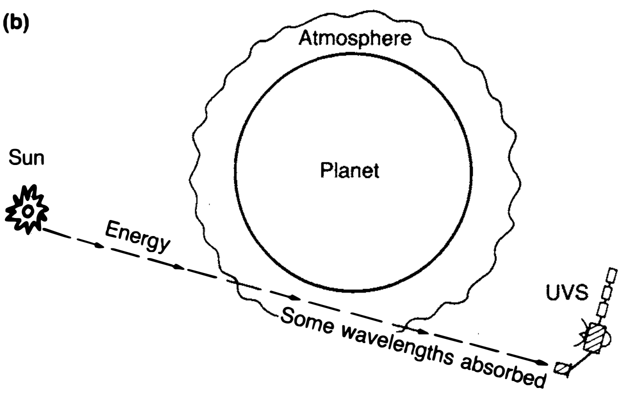
FIGURE 4
How Voyager 'sees' Neptune

(a)



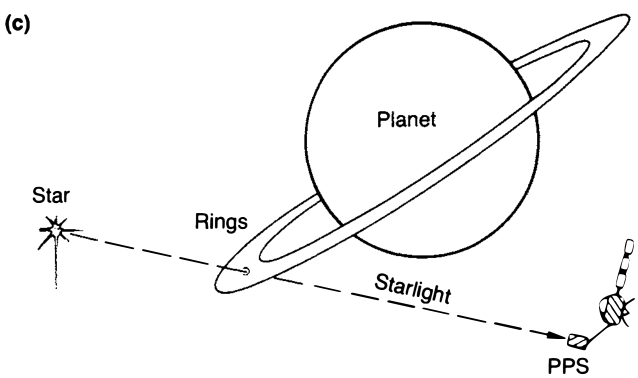
One of the most daring experiments Voyager performed at Neptune was to send a radio signal from the Radio Science Subsystem through the planet's atmosphere, during which time it would bend. The spacecraft had to arrive precisely on schedule, so its position relative to Earth would allow the signal to be received.

(b)



Measuring the atmosphere in the ultraviolet helps characterize the chemical composition of the material.

(c)



The photopolarimeter subsystem is a high-magnification telescope, which can see very small (1%) deviations in the light of stars, when the starlight passes through a ring. Using this instrument, scientists can estimate the particle size and extent of even tenuous rings, such as those at Neptune.

cameras can detect, many characteristics of Neptune's atmosphere and weather were revealed. In fact, because Neptune's atmospheric features were changing so rapidly, attempts to forecast the weather using the cameras became very frustrating.

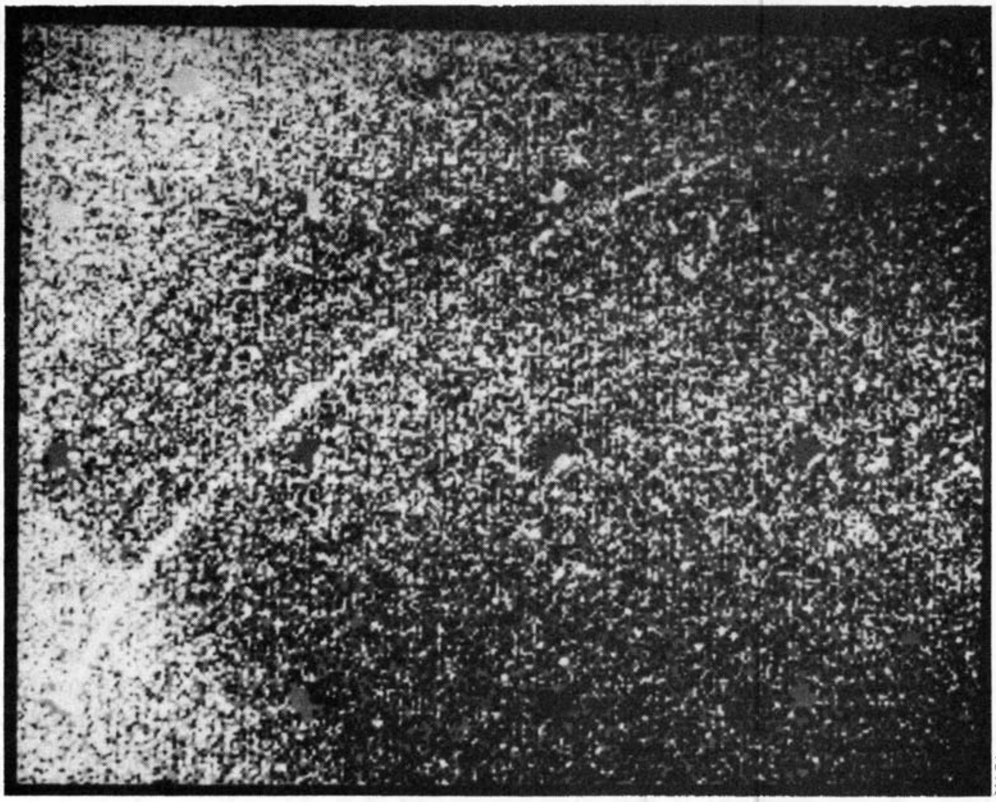
While, even the less detailed pictures of the dark spot showed structure inside, in the days before the close encounter and Voyager's passage behind the planet to conduct other experiments, imaging team head Bradford Smith said that measuring the changes in the white clouds, the vorticity of the material in the atmosphere, and the direction of the storm at the great dark spot could not be obtained just from the images. He said that, even looking at photographs taken a little more than two hours apart, the white clouds had moved and changed so much, that the scientists could not track any single feature. But scientists were able to estimate, as early as Aug. 24, that the white, high-altitude clouds are about 30 miles higher than the great dark spot, judging from an extraordinary and unique picture of shadows that the clouds cast on the darker storm spot below.

Then on Aug. 27, armed with data from other instruments, scientists were able to shed more light on Neptune's weather. One instrument, the photopolarimeter, is a telescope with various filters and polarization analyzers, which measures how its targets reflect light, and determines their properties, such as the reflected light polarized by chemicals and aerosols in the atmosphere. Three days after closest approach, Robert West from the University of Colorado reported that the photopolarimeter data reported that, in the ultraviolet range, Neptune looked somewhat bland, like Uranus, but unlike Jupiter or Saturn, meaning there are few ultraviolet-absorbing aerosols in the atmosphere.

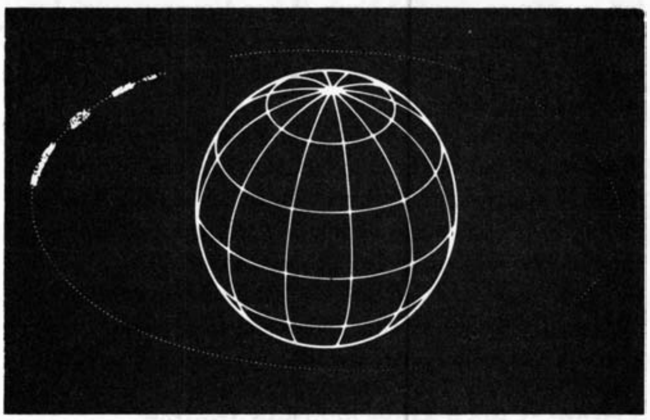
But Barney Conrath from NASA's Goddard Space Flight Center reported that, using the near-infrared filter, the instrument revealed different thermal or temperature levels in the atmosphere producing horizonal gradients, along with isolated warmer and colder spots. He explained that the gross thermal structure of the atmosphere determines how the wind varies with height, leading to wind shear zones, where the winds change to the opposite direction, such as east to west. Later analysis revealed hydrocarbon ices at the highest altitude of Neptune's atmosphere, beneath which are the condensed cloud layers. It was also found that the upper atmosphere is warmer than would be predicted, which is also true of the other giant planets.

The radio science team, which was still waiting the arrival of 992 pounds of magnetic tape with their data, reported at the final science briefing that preliminary data from its experiment (see Figure 4a) showed that the pressure in the dark spot methane clouds was lower than quoted, or 1.5 bars. The Earth's atmospheric pressure is 1 bar at sea level.

In order to conduct these measurements, the radio science system had to be exactly on target. The measurements are taken during an Earth occultation, when the Earth is on the opposite side of Neptune from Voyager. The timing for this



When Voyager photographed Neptune's rings on Aug. 19, it became clear why ground-based telescopes were unable to discern most of the three rings. In this 61-second exposure, the innermost ring can barely be distinguished from the background noise. The rings are not only extremely thin but are also coal-black in color.



experiment is so important, reported Len Tyler of the Center for Radar Astronomy at Stanford University, that if there had been an error of *16 seconds* in the timing of Voyager's arrival, the experiment would have been a complete failure! Voyager arrived at the appointed spot within two seconds of target.

Scientists reported that the great dark spot is an anticyclonic storm (rotating counterclockwise in the southern hemisphere), rolling in a shear zone like Jupiter's great red spot. It rotates around its own axis every 10 days, oscillates, and changes shape.

Retrograde (east-to-west) winds more than 700 miles per hour were measured, which are the strongest in the solar system—quite an active weather system on this cold, dark planet.

Finding the arcs and rings

Over the past ten years, astronomers using ground-based telescopes have made reliable reports of observing ring arcs around Neptune, six times. They did not believe they were seeing complete rings, because when they looked on the other side of the planet for the rest of the rings, they could not see them. It turned out that the rings are so thin in spots that it is not possible to completely observe them from Earth. Although the images taken by Voyager of the slight rings were beautiful, the details of their scope and composition could only be revealed by more precise experiments. The photopolarimeter was again brought into service.

With the ablility to see light in very high magnification, the photopolarimeter looked at Neptune's rings twice, taking advantage of the fact that the particles were blocking out the light of a star that was behind the rings. In total, Voyager scanned the region between 46,000 and 26,000 miles from the planet. The photopolarimeter first looked at the rings when the sunlight was shining directly on them as Voyager approached Neptune, seeing the reflected light of larger particles in back-scatter. Then, when Voyager went over the north pole and moved to the other side of the planet, with the rings lit from behind, the photopolarimeter could detect very slight changes in the starlight as the smaller rings' particles reflected light in forward-scatter, which is similar to the phenomenon in which the light from small particles on the windshield of a car at night is scattered forward into the passengers' eyes, and not back out from the window.

The photopolarimeter revealed that there are three complete rings at Neptune, and one wide sheet of very thin ring material. Carolyn Porco, from the University of Arizona, summarized the ring findings, stating that the three rings are 26,000 miles, 32,000 miles, and 39,000 miles from the planet. The sheet or plateau of ring material stretches between about 32,000-36,000 miles. The middle ring was entirely new, as it did not correspond to any of the ground-based observations. The photopolarimeter indicated that the middle and inner rings are between 40-60% dust.

The more mysterious outer ring is 60% dust in the clumpy "arc" regions, and perhaps 30% dust in the barely visible, non-arc regions. This ring, which had been seen only as arcs from Earth, turned out to be very thin in some regions, and quite clumpy in others. Scientists reported that this structure was reminiscent of the braided outer F ring of Saturn.

Don Gurnett reported that when the plasma wave experiment "looked" at the rings, it found that there were many small particles detected in the 10-15 minutes before the rings' place crossings, both inbound and outbound. A dense core of particles was detected for 10 minutes during the crossing, but in addition, for two hours before Voyager crossed the ring plane, the instrument indicated a region of low-density matter which indicated that Neptune has a "halo" of dust particles around it.

There is little question that, like Saturn's rings, the rings, the plateau, and the halo features of Neptune constitute a dynamic system. Unlike Saturn, however, no gaggle of numerous small satellites, which could "shepherd" the rings and hold them in place, has yet been found at Neptune. As Carolyn Porco stated, scientists still do not understand the dynamics of Saturn's F ring. Now, they have Neptune's ring system to try to figure out, as well.

'America's destiny to pioneer in space'

At a press conference held at the Jet Propulsion Laboratory on Aug. 26, Dr. Leonard Fisk, NASA Associate Administrator for Space Science and Applications, stated that the Voyager 2 Neptune encounter was the "end of an era," because "it is the last time we will see a planet for the first time." (Pluto is not considered a regular planet of the Solar System.) Over the next decade, he said, NASA will send spacecraft to four planets, not to fly by, but to go into orbit. After being launched from the Space Shuttle on May 4, the Magellan spacecraft is on its way to Venus, where it will map the planet's shrouded surface using radar that "sees" through the clouds.

On Oct. 12 the Shuttle is scheduled to launch the Galileo spacecraft which will orbit Jupiter and send a probe into its atmosphere. Galileo was on its way to the launch pad at Cape Canaveral at the moment Voyager was at Neptune. The Cassini mission to Saturn will send a probe into the atmosphere of its moon Titan, and will orbit the ringed planet. The Mars Observer, scheduled for a September 1992 launch, will also be an orbiter, perhaps

Triton: 'Like a Mars orbiting Jupiter'

On Aug. 22, when only the fuzziest pictures of Triton had been sent by Voyager, imaging team head Bradford Smith prophetically stated to the press that the interesting methane bands in the atmosphere, and albedo (light reflectance) pattern of Neptune's moon was like Mars. As Voyager came closer, other features started to appear, including a darker equatorial zone, a bluish area bright in ultraviolet emission, and a mottled region. Considering that the haze and atmosphere on Saturn's moon Titan (the only other moon in the Solar System with an atmosphere) prevented Voyager from photographing its surface, scientists were hoping the details starting to emerge from Triton were not just atmospherics.

The day after the closest fly-by of Neptune and then of Triton five hours later, Larry Soderblom of the U.S. Geological Survey, stated at the science briefing: "What a way to leave the Solar System!" The relation of the two is "like Jupiter being orbited by Mars," he stated, as he showed pictures with evidence of volcanism, fractures, regions turned into flat planes from flowing material, a network of ridges, a bluish fringe around the south pole, frosted regions, haze, and volcanic calderas with multiple layers of material.

Bill Sandel, from the University of Southern California, reported the next day that for ten years, ground-based observations had seen the signature of methane at Triton, but it was unclear whether the methane is in the atmosphere or on the surface. From Voyager's ultraviolet instrument readings, he reported, we now know that the atmosphere of Triton is mostly molecular nitrogen, with some ionized nitrogen, as well. From stellar occultations, which observe how the atmosphere absorbs starlight, Voyager revealed that the methane is just above the surface.

On Aug. 27, three days after closest approach, Soderblom reported more detail on the geological terrain of Triton. There is evidence of both global "oceanic" flooding on Triton, he said, as well as localized eruptions of liquid from inside the moon. In calderas, which are the craters on the top of volcanos, there are multiple levels, as if molten fluids had risen and then solidified on the floor of the crater, then melted and froze again repeatedly. Similar layering from melting looking for suitable landing sites for future manned missions. Next year NASA will launch the long-awaited Hubble Space Telescope which, while it orbits the Earth, will see more detail in planetary space than any telescope before it. It will be able, for example, to see Jupiter in the same detail as the Voyagers did on their quick fly-bys. Thirty-five science payloads carrying hundreds of experiments will go into space during the next five years. This is "the highest launch rate for science missions," he said, "in the history of the space program."

The day before, Vice President Dan Quayle, who heads the National Space Council, spoke to the employees at JPL who had made the Voyager mission possible. After congratulating the staff—they had just learned hours earlier that the encounter had been "picture perfect"—Quayle stated, "It is America's destiny to discover and pioneer in space." Quayle stated that the space program "leads to economic growth," and is a "high-yield investment in America's future." He stressed that America must reassert its leadership in space. The Moon, he said, could be a springboard to take us farther into the Solar System, and Mars is a "perfect laboratory." During a press conference following his speech, Quayle stressed that although the administration is interested in international cooperation, and that he would discuss space exploration during his trip to Japan in mid-September, "America should be number one; the U.S. will take the lead."

The following day, speaking after Dr. Fisk was Dr. Lew Allen, the director of the Jet Propulsion Laboratory. Allen directly addressed the unfounded fears of the space science community that an aggressive manned space program would squeeze out their unmanned scientific research—a fear which is often fed by the likes of space quack Carl Sagan, who has for years insisted that the manned program has no scientific value, but is basically a publicity stunt. Allen stated that JPL will be an "enthusiastic participant" in the space initiative outlined by President Bush, to go back to the Moon and on to Mars. Who knows, he mused, some day "we may do science at a lunar base."

Until now, only the inner planets, our Moon, and Mars, have had our intelligence, in the form of robotic spacecraft, observe them over time. The Voyagers' grand tour of the outer Solar System was a once-in-a-lifetime opportunity, and had given us an enticing first quick look at the giant outer planets. In the next Golden Age of space science, more will be learned about places we intend to visit ourselves, such as the Moon and Mars, and about the farthest objects in the universe, through a series of great observatories in space. But we will also have a chance to revisit Jupiter and Saturn, among the gas giants, and revise what we have learned from the Voyagers' eyes and ears.

and freezing is seen at the poles of Mars. Soderblom put forward a theory that a few dozen feet below the surface of Triton, nitrogen may exist in liquid form. For years, scientists thought that the temperature of Triton would be at the triple point of nitrogen—the point where it can exist in gaseous, liquid, and solid form, like water on Earth, and that they might see lakes of liquid nitrogen on the surface. However, since Triton's surface temperature is apparently only *30° above absolute zero*, the nitrogen exists only in solid form under ambient pressure. But under the surface, the pressure might be great enough to liquefy the nitrogen. If there were a break somewhere on the surface, and a localized drop in pressure, the liquid nitrogen could "explode" through a volcanic-type vent, spewing plumes of nitrogen vapor and crystals upward.

In the south polar region of Triton, Voyager did spot 20-30 plumes of darker material in the atmosphere. Scientists, including those who have been working to understand the volcanoes on Jupiter's moon Io, quickly tried to estimate the conditions under which nitrogen volcanoes on Triton might exist. Unlike Io, the volcanic activity on Triton would not be driven by heat, but could be described as an artesian volcano, where pressure causes a phase-change and eruption. Quick calculation showed that liquid nitrogen exposed to a vacuum would produce a discharge at about 800 feet per second, which would extend about 25 miles, composed 80% of ice particles, and 20% of vapor. If a wind were blowing at about 320 feet per second, it has been estimated, the material would form plumes. These plumes may become dark, Soderblom speculated, when the ice particles pick up methane from the throat of the volcano.

Radio science data revealed that Triton's atmosphere extends to an altitude of about 220 miles, similar to Earth. The moon's density indicated that, like Pluto, it is about two-thirds rock. The atmospheric pressure is about one one-thousandth that of Earth, and its extremely low temperature makes it the coldest object yet observed in the Solar System.

Are the volcanoes still active? That question may not be able to be answered with Voyager's data. Scientists still do not even know if the volcanoes are active on Mars, where we have not only produced close-up images, but have even landed two spacecraft!

Without doubt, Triton is one of the most interesting places in Earth's family of heavenly bodies. Although we will not send spacecraft there again soon, we can expect more surprising revelations about this frozen but dynamic world, as scientists pore over the wealth of data returned by Voyager for years to come.