(NASA-CR-185317) VOYAGER AT NEPTUNE: 1989
(Jet Propulsion Lab.) 20 p CSCL 22B

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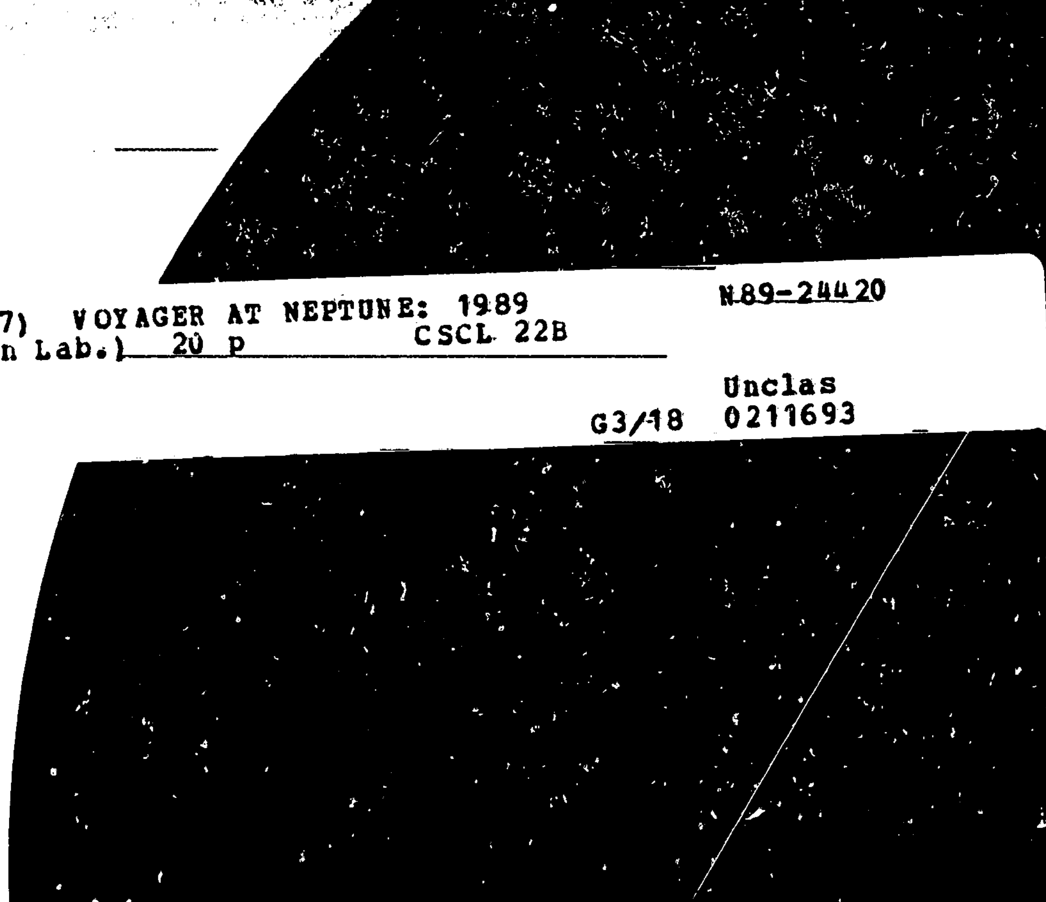

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Voyager 2 will fly past Neptune and its large moon Triton on August 24, 1989 Pacific Daylight Time (PDT), flashing over the planet's north pole at an altitude of about 4,850 kilometers (3,000 miles). Five hours later, the spacecraft will pass about 38,000 kilometers (23,600 miles) from Triton.

The close flyby of Neptune will bend Voyager 2's flight path sharply, sending it below the ecliptic plane at an angle of about 48 degrees.

Both spacecraft are expected to return valuable data well into the twenty-first century. By about the year 2020, the electrical power supplied to the Voyagers by their nuclear power sources is expected to have dwindled sufficiently to end the lives of the spacecraft. Eventually, the Voyagers will pass out of the solar system and cruise silently toward the stars.

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Note: The actual moment of closest approach will be on August 24, 1989 at 9 P.M. PDT. The spacecraft's radio signals at closest approach will not reach Earth until August 25, 1:06 A.M. PDT, since radio signals (traveling at the speed of light) will take 4 hours 6 minutes to cross the vast distance from Neptune to Earth. Many of the observations conducted about this time will be recorded on the space-

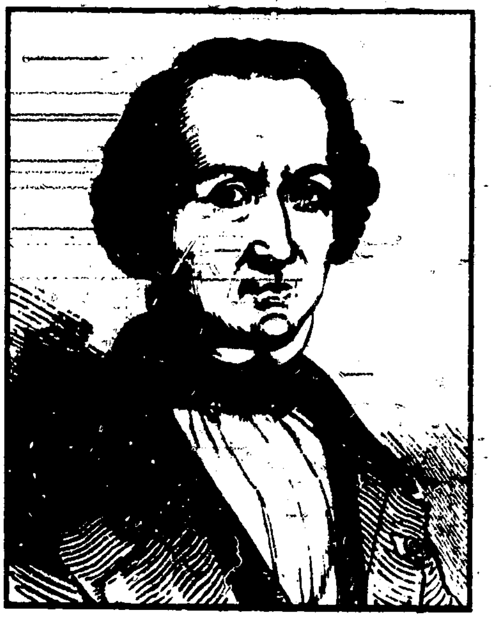
Neptune was the first planet located through mathematical predictions rather than through systematic observations of the sky.

In the years following William Herschel's discovery of Uranus in 1781, astronomers noted that Uranus was not faithfully following its predicted path. Uranus seemed to accelerate in its orbit before 1822 and to slow after that. One possible explanation was that the gravity of an undiscovered planet was affecting the orbit of Uranus.

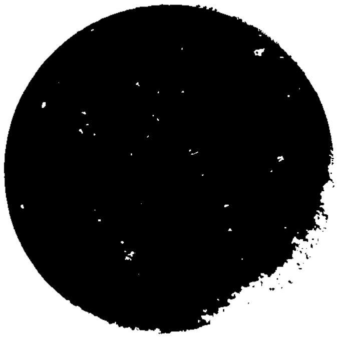
Two young mathematicians, each working independently and with no knowledge of the other, were intrigued by the mystery and set out to solve it.

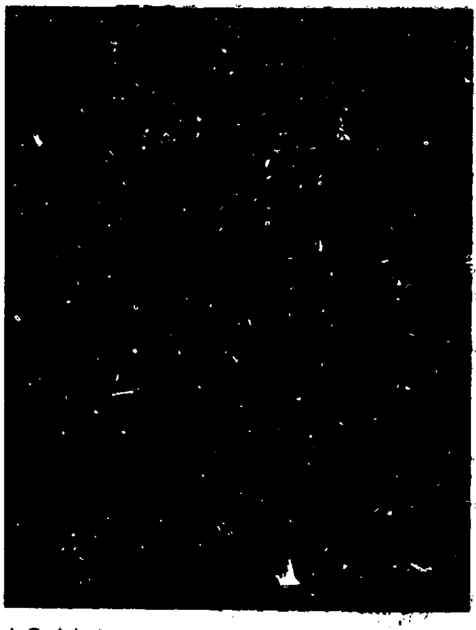
In England, John Couch Adams began work on the problem in 1841 and pursued it sporadically. By the fall of 1845, he felt confident enough in his calculations to present them to the Astronomer Royal, Sir George Airy, at the Greenwich Observatory. It was, perhaps, Adams' youth and the fact that he was an unknown astronomer that caused the older man to give little attention to Adams' work at the time.

The [illegible] French mathematician Urbain Jean Joseph Le Verrier published his own work on the topic. When Sir George noticed that Le Verrier's work closely matched that of young Adams, he directed Professor James Challis of Cambridge Observatory to begin a search of the heavens for this object. Challis was hindered, however, by the lack of up-to-date star maps of the area to be searched and, without these, it was difficult to quickly discern new bodies from known ones. His only course was to tediously scan and re-scan the sky over a period of weeks, watching for planet-like motion. He missed recognizing Neptune several times.

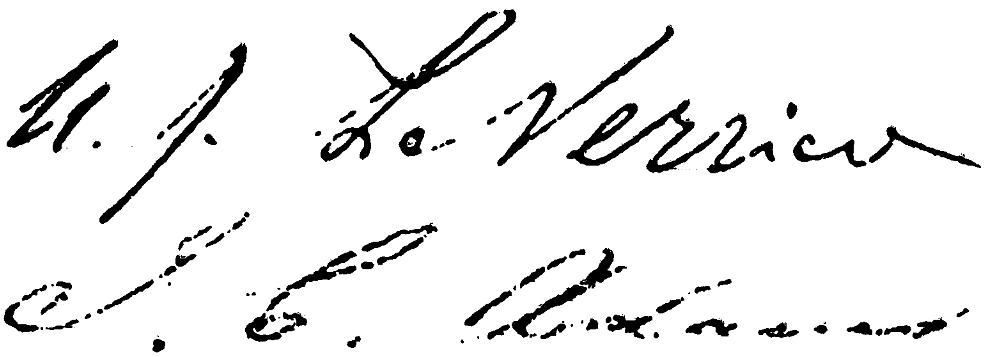


U. J. J. Le Verrier
(From the *Illustrated London News*, Feb. 2, 1847.)





J. C. Adams
(From R. Ball, *Great Astronomers*, London, 1895.)



	Obs. – Theory		Obs. – Theory		Obs. – Theory
1780	+0.27	1801	–0.04	1822	+0.30
1783	–0.23	1804	+1.76	1825	+1.92
1786	–0.96	1807	–0.21	1828	+2.35
1789	+1.82	1810	+0.56	1831	–1.06
1792	–0.91	1813	–0.94	1834	–1.44
1795	+0.09	1816	–0.31	1837	–1.62
1798	–0.99	1819	–2.00	1840	+1.73

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In September 1846, Le Verrier, unable to interest French astronomers, sent his calculations to an assistant at the Berlin Observatory, Johann Gottfried Galle. Galle received the letter on September 23 and began a search for the object that night. Galle, too, might have missed the discovery had not a student, Heinrich Louis d'Arrest, provided him with the latest star map of the area. And there, within a degree of Le Verrier's predictions (and only a few degrees from Adams' predictions) was an unidentified disk. When, by the next night, the object had a new position, the discovery could be claimed —an eighth planet had been found.

An international brouhaha followed, with supporters of Adams contending with those of Le Verrier for recognition of their champion. In keeping with the established practice of naming planets for ancient Roman or Greek gods, however, the new planet was called Neptune, after the Roman god of the sea.

Seventy-five years earlier or later, the problem would have been mathematically insoluble. At the time of the discovery, Neptune was in the one part of its orbit that allowed solution.

The orbit calculated by Adams and Le Verrier is not precisely Neptune's orbit. Differences between the actual and predicted orbits continued to be noted by astronomers. In 1915, American Percival Lowell predicted a ninth planet, based on the differences between calculated and observed orbits of Neptune and other planets. Motivated by Lowell's ideas, V. M. Slipher, the director of Lowell Observatory in Flagstaff, Arizona, hired astronomer Clyde Tombaugh to begin an exhaustive search for this ninth planet. In 1930, 84 years after Neptune's discovery, Tombaugh discovered the planet Pluto. Pluto is now known to be far too small to have caused the apparent differences between Neptune's predicted and observed orbits, however, and the source of these differences remains unresolved.

Berlin Observatory as it was at about the time Neptune was discovered in 1846. (From Verlag G. Gropius, Berlin, 1833, Märkisches Museum.)

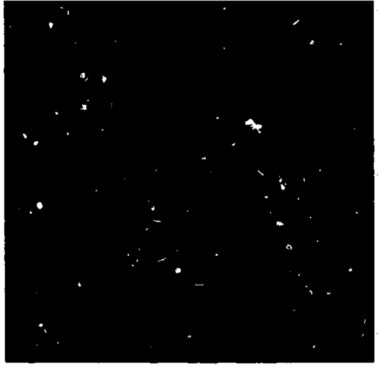
Uranus and Neptune are often thought of as a pair, because of their great distance from the Sun and their similarities in size and color. But already scientists expect that Neptune will be vastly different from any of the other planets yet studied.

Although Neptune is the fourth largest planet, it is invisible to the naked eye because it orbits in the outer regions of the solar system, 4½ billion kilometers (nearly 3 billion miles) from the Sun. (In fact, Neptune is currently the farthest planet from the Sun—since the early 1970s, Pluto has been closer to the Sun than Neptune has, and it will remain so until the end of this century.)

At this distance, Neptune receives nearly 1,000 times less sunlight than Earth, and about two and one-half times less than Uranus, but its overall temperature is about the same as that of Uranus. Therefore, scientists believe that Neptune must have some internal heat of its own, as do Jupiter and Saturn.

Neptune's seasons last more than 40 years. Its rotational axis is tilted about 30 degrees to the plane of its orbit around the Sun (Earth's axis tilts 23.5 degrees). At this phase in Neptune's sojourn around the Sun, it is summer in the southern hemisphere and there is continuous daylight at the south pole, while the north pole is cloaked in darkness.

Both planets rotate at about the same rate—Uranus' internal rotation rate is 17 hours 14 minutes, while Neptune's atmospheric rotation rate is between 17 and 18 hours. Rotation rates of planets can be measured in two ways: by tracking cloud features in the atmosphere or by monitoring the radio emissions generated by electrons spiraling into the planet's magnetic field. Radio emissions give the rotation rate of the bulk of the planet because the magnetic field is generated in the planet's interior.



Cloud structure on Neptune is shown in an image taken in January 1989 from about 309 million kilometers (185 million miles).

Voyager 2 captured this inbound view of Neptune and Triton on May 9, 1988 from 685 million kilometers (426 million miles).

Neptune looms above the surface of Triton, where shallow pools of liquid nitrogen may form beneath a thin atmospheric haze. (Reprinted with permission from *National Geographic Magazine* and artist Paul Hudson.)

Measurements obtained by tracking cloud features include the additional effects of atmospheric winds. As Voyager 2 nears Neptune, the planetary radio astronomy experiment will determine the rotation rate of the planet's interior.

With an equatorial diameter of about 49,400 kilometers (30,700 miles), Neptune is only slightly smaller than Uranus. But Neptune is denser, indicating that it must contain a larger quantity of heavier materials than does Uranus.

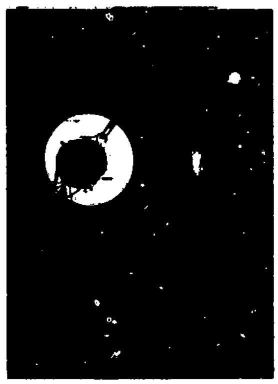
Like Uranus, Neptune is believed to be composed primarily of rock and melted ice, mixed with hydrogen and helium. The combination of infrared and radio observations will provide a measurement of the relative amounts of helium and hydrogen in Neptune as compared with the amounts in the other gaseous outer planets and the Sun.

Despite Neptune's remoteness, astronomers have been able to learn a few things about the planet's atmosphere. (Light emitted and reflected from an atmosphere contains information about the atmosphere's chemistry and composition.) At times, high-resolution images taken from Earth-based telescopes indicate the existence of thin atmospheric hazes over major portions of the planet. The haze, which comes and goes in a matter of days or weeks, may consist of methane ice crystals.

If there are methane clouds on Neptune, they probably condense at a pressure of about 2 bars (twice the atmospheric pressure at sea level on Earth) and a temperature of about 85 kelvins (−305°F). Voyager 2's radio signals can probe to a pressure level of 3 to 5 bars, so there is a good chance of detecting the base of the methane clouds, which will indicate the amount of methane in Neptune's atmosphere. Although other cloud layers, including water-ice clouds, are expected deeper in the atmosphere, Voyager 2 will not be able to detect them. While the spacecraft is in Neptune's shadow, it will maneuver to precisely track the outer edge of the planet to enable Voyager's radio signal to probe Neptune's atmosphere.

There is evidence that Neptune has a magnetic field, as do Mercury, Earth, Jupiter, Saturn, and Uranus. Voyager 2 is not likely to penetrate the planet's magnetosphere until the last day before the spacecraft's closest approach to the planet.

Neptune's interior is believed to consist of a mixture of melted ices and rock.



As Voyager 2 dips behind Neptune, the ultraviolet instrument will study the atmosphere as sunlight streams through it.

Voyager 2 bids farewell to a crescent Neptune.

Neptune has two known satellites, Triton and Nereid. Neither travels in the plane of the planet's equator—Triton's orbital plane is at an angle of about 20 degrees to Neptune's equator, while Nereid's is at an angle of about 30 degrees.

Triton completes one rotation on its axis in the same amount of time that it takes to circle Neptune, 5.88 Earth days. Because the rotation rate is synchronized with its orbital period, the same hemisphere always faces Neptune. (Similarly, Earth's Moon is also in synchronous rotation, keeping the same face toward Earth.)

At an average distance of 354,600 kilometers (220,300 miles) from the center of its planet, Triton is nearly as far from Neptune as the Moon is from Earth. Triton is the only large moon in the solar system with a retrograde orbit; that is, it travels in the direction opposite the planet's rotation. Because of its retrograde orbit, Triton is spiraling slowly toward Neptune.

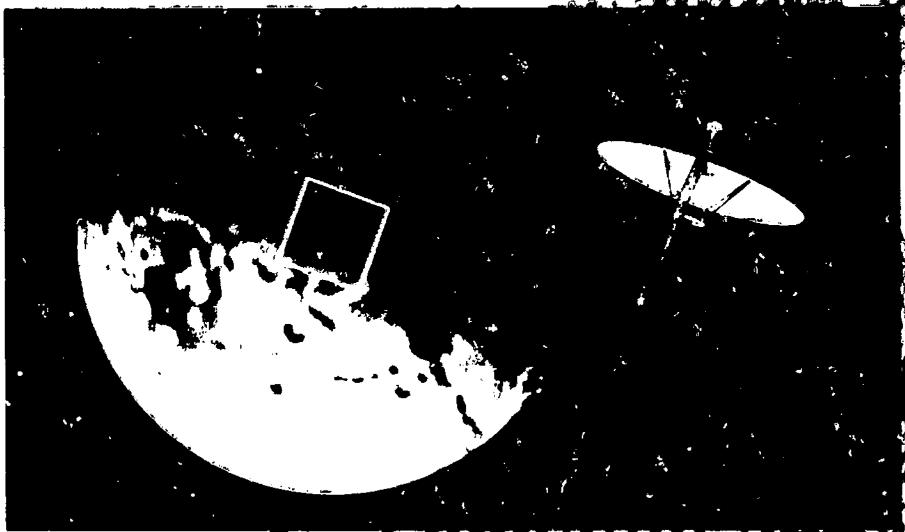
Triton is roughly the size of Earth's Moon. Estimates of Triton's diameter range from 2,200 to 4,000 kilometers (1,400 to 2,500 miles).

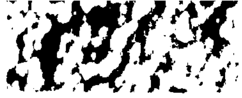
If Triton is small—perhaps about 2,200 kilometers (1,400 miles) in diameter—scientists expect to find only a very thin atmosphere. If, on the other hand, Triton is larger—perhaps about 4,000 kilometers (2,500 miles) in diameter—then it is expected to have a lower surface temperature and could have a thicker atmosphere (which otherwise would have escaped to space long ago), and Voyager's cameras may not be able to see the surface.

Because Triton's size is uncertain, the Voyager flight team has prepared primary and alternative designs for some observations. This strategy will allow a critical decision just a few days before the encounter, based on the latest information available: if Triton is large and has a thick atmosphere, observations will be concentrated on the atmosphere; if Triton is smaller and the atmosphere thin, observations instead will be concentrated on the surface. The best Voyager images of Triton are expected to show features smaller than one mile.

Small quantities of methane may be dissolved in shallow pools of liquid nitrogen on Triton's surface.

An hour before Voyager 2's closest approach to Triton, the field of view of the narrow-angle camera will cover an area about 700 kilometers (400 miles) square.





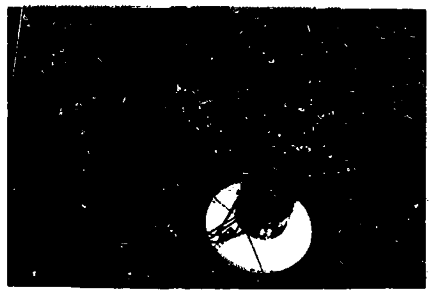
Scientists hope that Voyager 2's cameras will be able to see through Triton's atmosphere to the surface, where there is methane frost or ice and solid or liquid nitrogen. Small quantities of methane may also be dissolved in ponds of liquid nitrogen. On the dark side of Triton, Voyager 2 will look for temperature differences that may indicate the existence of liquid bodies. (Since liquids cool more slowly than fine-grained solids, warmer areas on the dark side might be liquid.)

Triton's seasonal cycle is complex and extreme because of the combined effects of its orbit and its rotation. Each of Triton's poles spends long periods in darkness, where temperatures are extremely low and most molecules are frozen. Where the Sun is directly overhead on Triton, the temperature is near the freezing point of liquid nitrogen

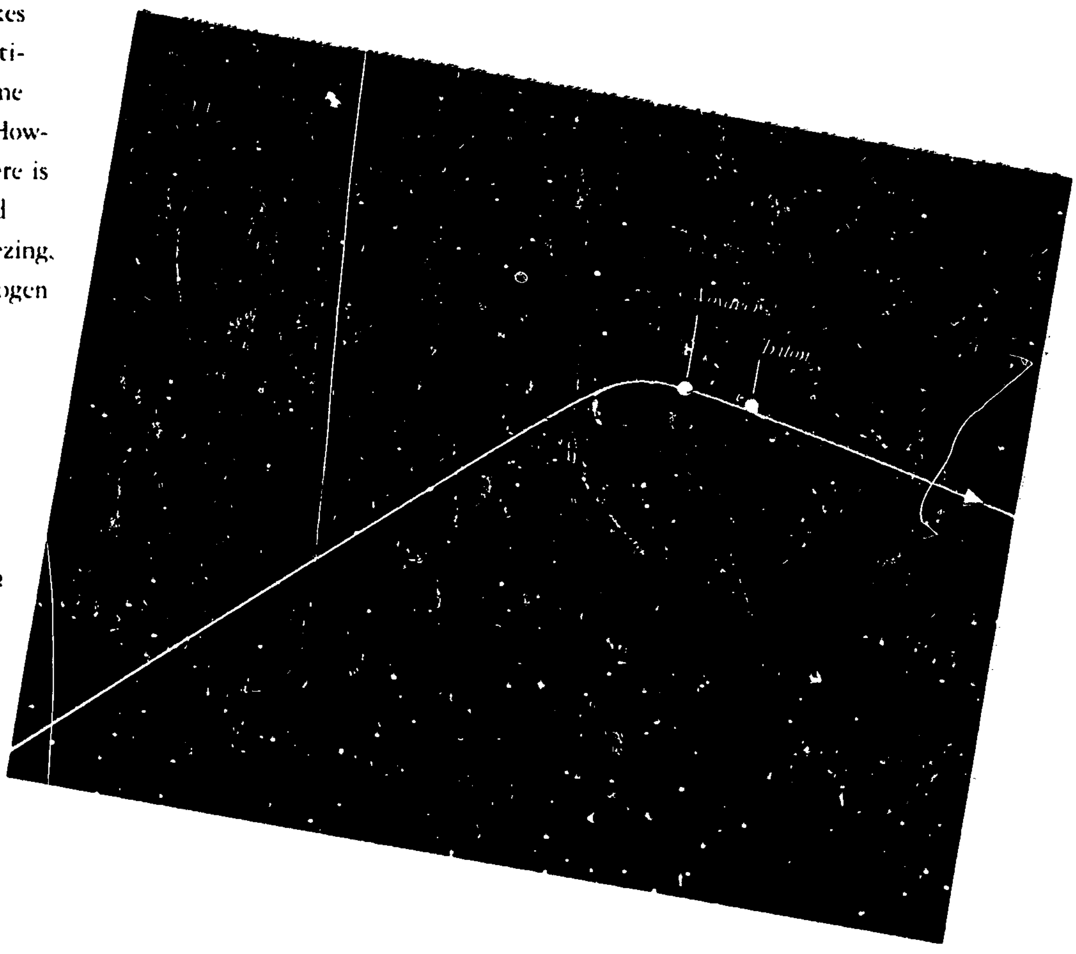
(63 kelvins or −346°F). The southern hemisphere of Triton is now approaching summer, and sunlight currently strikes directly at about 40 degrees south latitude. As this hemisphere warms, some liquids and solids vaporize quickly. However, as Triton rotates, this hemisphere is plunged alternately into darkness and daylight, and this too affects the freezing, melting, and vaporization of the nitrogen and methane.

Voyager 2 is slated to pass through a narrow area behind Triton where both the Sun and Earth will be hidden from view for about 4 minutes. During this time, the ultraviolet spectrometer on board the spacecraft will study the satellite's atmosphere by viewing the Sun shining through Triton's atmosphere while, at the same time, the spacecraft's radio beams will probe the atmosphere to determine temperature and pressure levels. Just days before closest approach, navigators will instruct Voyager 2 to fine-tune its flight path to target for this area of Triton's shadow; this adjustment will be based on the best estimates of the location and size of Triton and on the gravitational effects of Neptune on the flight path.

Nereid, which is between 300 and 1,100 kilometers (190 and 680 miles) in diameter, travels around Neptune in a highly elliptical orbit that ranges from 1,390,000 to 9,635,000 kilometers (860,000 to 5,990,000 miles). Voyager 2's closest flyby distance to Nereid will be about 4,655,000 kilometers (2,890,000 miles). Even at that range, Voyager may discern bright and dark areas on Nereid's surface.



Heading below the ecliptic, Voyager 2 will look back at the crescents of Neptune and Triton.



Five hours after encountering Neptune, Voyager 2 will swing past the large moon Triton.

Both Voyager spacecraft have survived in space for almost 12 years and, although each has experienced some hardware failures, they are still in good health and capable of returning valuable scientific data well into the next century.

Each spacecraft carries instruments for ten scientific investigations. In addition, the spacecraft's radio is used as an instrument for an eleventh scientific investigation.

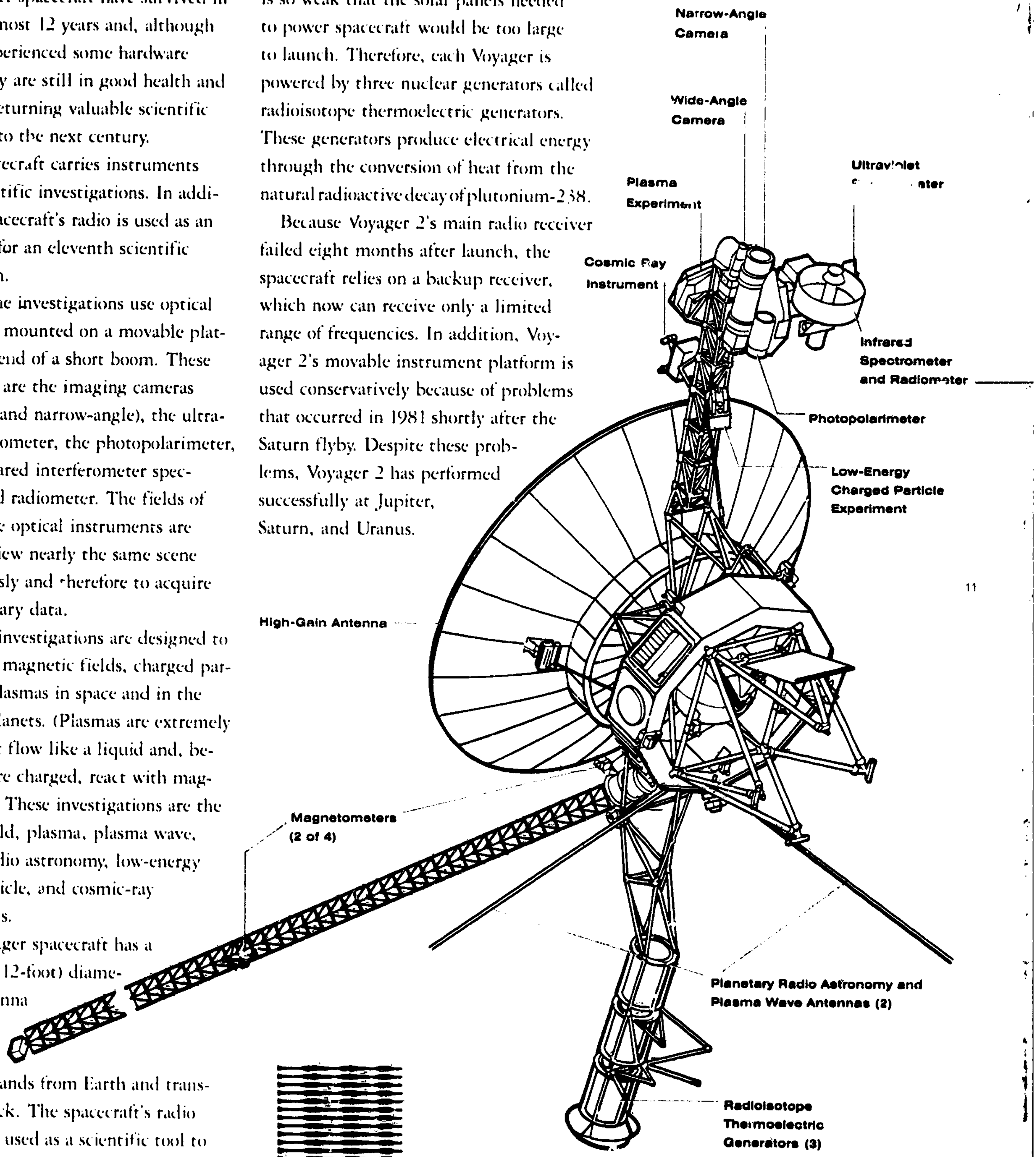
Four of the investigations use optical instruments mounted on a movable platform at the end of a short boom. These instruments are the imaging cameras (both wide- and narrow-angle), the ultraviolet spectrometer, the photopolarimeter, and the infrared interferometer spectrometer and radiometer. The fields of view of these optical instruments are aligned to view nearly the same scene simultaneously and therefore to acquire complementary data.

Six more investigations are designed to measure the magnetic fields, charged particles, and plasmas in space and in the vicinity of planets. (Plasmas are extremely hot ions that flow like a liquid and, because they are charged, react with magnetic fields.) These investigations are the magnetic field, plasma, plasma wave, planetary radio astronomy, low-energy charged particle, and cosmic-ray investigations.

Each Voyager spacecraft has a 3.66-meter (12-foot) diameter dish antenna through which it receives commands from Earth and transmits data back. The spacecraft's radio signal is also used as a scientific tool to study atmospheres, rings, and gravitational effects.

Beyond the orbit of Mars, sunlight is so weak that the solar panels needed to power spacecraft would be too large to launch. Therefore, each Voyager is powered by three nuclear generators called radioisotope thermoelectric generators. These generators produce electrical energy through the conversion of heat from the natural radioactive decay of plutonium-238.

Because Voyager 2's main radio receiver failed eight months after launch, the spacecraft relies on a backup receiver, which now can receive only a limited range of frequencies. In addition, Voyager 2's movable instrument platform is used conservatively because of problems that occurred in 1981 shortly after the Saturn flyby. Despite these problems, Voyager 2 has performed successfully at Jupiter, Saturn, and Uranus.



The communications link with the spacecraft is provided by a system of three radio-telescope complexes located around the world; this system is NASA's Deep Space Network (DSN), managed by JPL. These complexes are strategically located near Barstow, California; Madrid, Spain; and Canberra, Australia, so that at all times, as the Earth rotates, at least one station can communicate with the spacecraft. Because of Voyager 2's location in the sky, antennas in the southern hemisphere (Australia) will have the best "view" of Voyager 2 during the Neptune encounter.

The radio signals from the Voyager transmitters (which have about the same wattage as the light bulb in a refrigerator) get progressively fainter as the two spacecraft speed away from Earth. To track these faint signals, larger antennas and more sensitive receivers are needed on Earth; in addition, more power is needed to transmit commands to the spacecraft across the vast distance.

To meet these needs, all of the DSN antennas have been upgraded considerably since the Voyager spacecraft were launched in 1977. Although Voyager 2 will be 1.6 billion kilometers (1 billion miles) farther away, the communication rates at Neptune will be about the same as they were at Uranus due to these improvements and new techniques. Each DSN complex has three antennas that may be used to communicate with the Voyagers. Since the Uranus encounter in 1986, the largest antennas have all been enlarged from 64 to 70 meters (210 to 230 feet) in diameter. Also since 1986, a new 34-meter (112-foot) diameter antenna has been built at the Madrid station, matching the configuration that exists at the Californian and Australian complexes.

The DSN can also increase the data return by combining the spacecraft signals received at several antennas, thereby effectively forming one giant antenna. During the Uranus encounter, the Australian government's 64-meter Parkes Radio Astronomy Telescope was arrayed with the Canberra DSN complex to assure better data capture from Uranus.

For the Neptune encounter, preparations are being made for use of the twenty-seven 25-meter (82-foot) antennas of the Very Large Array (VLA) near Socorro, New Mexico; the Parkes Radio Observatory near Canberra, Australia; and the Usuda Observatory in Japan.

Parkes will once again be linked with Canberra, while the VLA will be arrayed with Goldstone, near Barstow, California. The Usuda antenna will provide additional tracking for the critical radio science observations during closest approach.

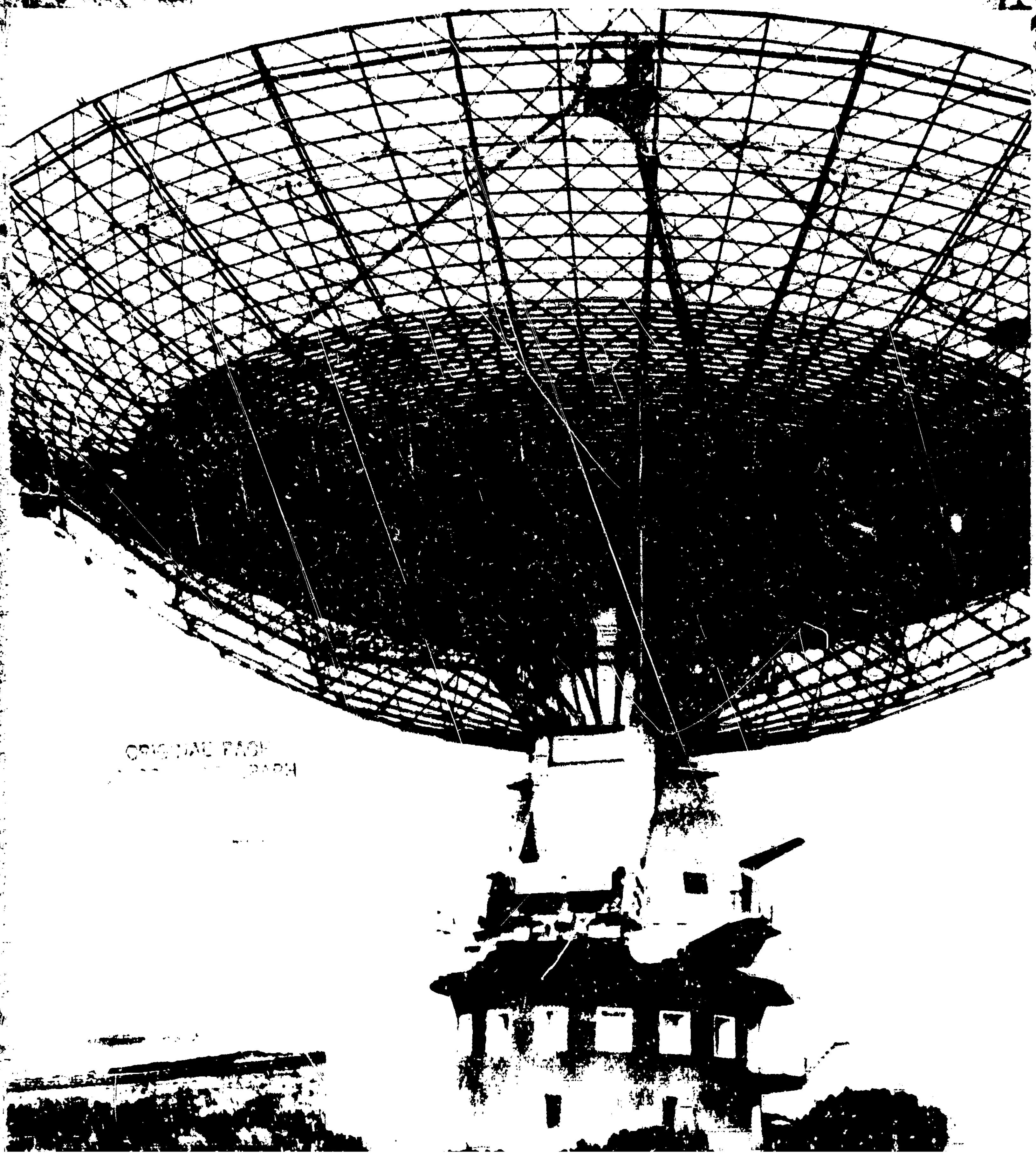
The Parkes Radio Observatory is operated by the Commonwealth Scientific and Industrial Research Organization (CSIRO).

The Very Large Array is part of the National Radio Astronomy Observatory, which is operated by Associated Universities, Inc. for the National Science Foundation.

The Institute of Space and Astronautical Science (ISAS) of Japan operates the 64-meter (210-foot) antenna at Usuda on the island of Honshu, Japan.

Signals received at the Parkes Radio Observatory near Tidbinbilla, Australia, will be combined with signals received at the nearby DSN station.

The 27 antennas of the Very Large Array near Socorro, New Mexico, form one large "ear" to listen to Voyager.



The first spacecraft encounter with the eighth planet in the solar system presents a number of challenges and special circumstances.

Data Rate

As spacecraft travel farther from Earth, the rate at which the DSN antennas can reliably receive the data decreases. For example, during Voyager 2's Jupiter encounter, when the spacecraft was over 900 million kilometers (about 560 million miles) from Earth, the highest data rate was 115,200 bits per second. At Neptune, nearly 4½ billion kilometers (3 billion miles) from Earth, the highest data rate will be 21,600 bits per second. To increase the amount of data that can be reliably returned, flight engineers have devised ways to reduce the number of bits required to transmit images. These include changing the way the spacecraft encodes the data before it is edited, compressed, and transmitted.

Late Updates

A major task will be to deliver Voyager 2 to the right place at the right time. Any deviation could mean loss of irreplaceable observations — Neptune and Triton will not be visited again for a very long time.

To provide Voyager 2 with the latest possible pointing and timing knowledge, the flight team at JPL must perform a number of activities very late in the encounter period, often sending updates to the spacecraft after it has begun performing the current set of instructions. These updates will provide the spacecraft with the latest and best possible information on precisely where to find the targets at predetermined times.

The Images

At Neptune, where light levels are nearly 1,000 times dimmer than those at Earth and 33 times dimmer than those at Jupiter, camera shutters must be open longer to gather more light. Combined with the motion of both the spacecraft and the target body, this can result in badly smeared images.

Several methods to reduce image smear have been developed: image-motion compensation, steadying the spacecraft, and new procedures on the ground and on the spacecraft.

Three techniques have been developed to compensate for the motion of the spacecraft and its targets during imaging. They include continuously turning the entire spacecraft to track the target during a series of exposures, "nodding" the spacecraft to track the target only during each exposure, or slowly moving the instrument platform during an exposure.

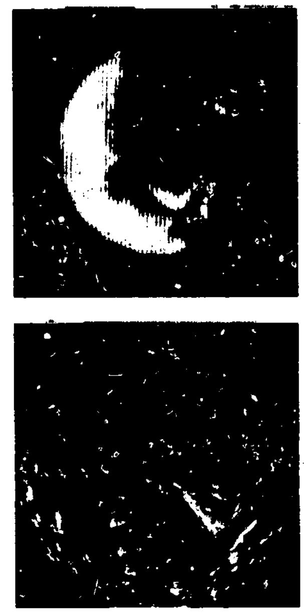
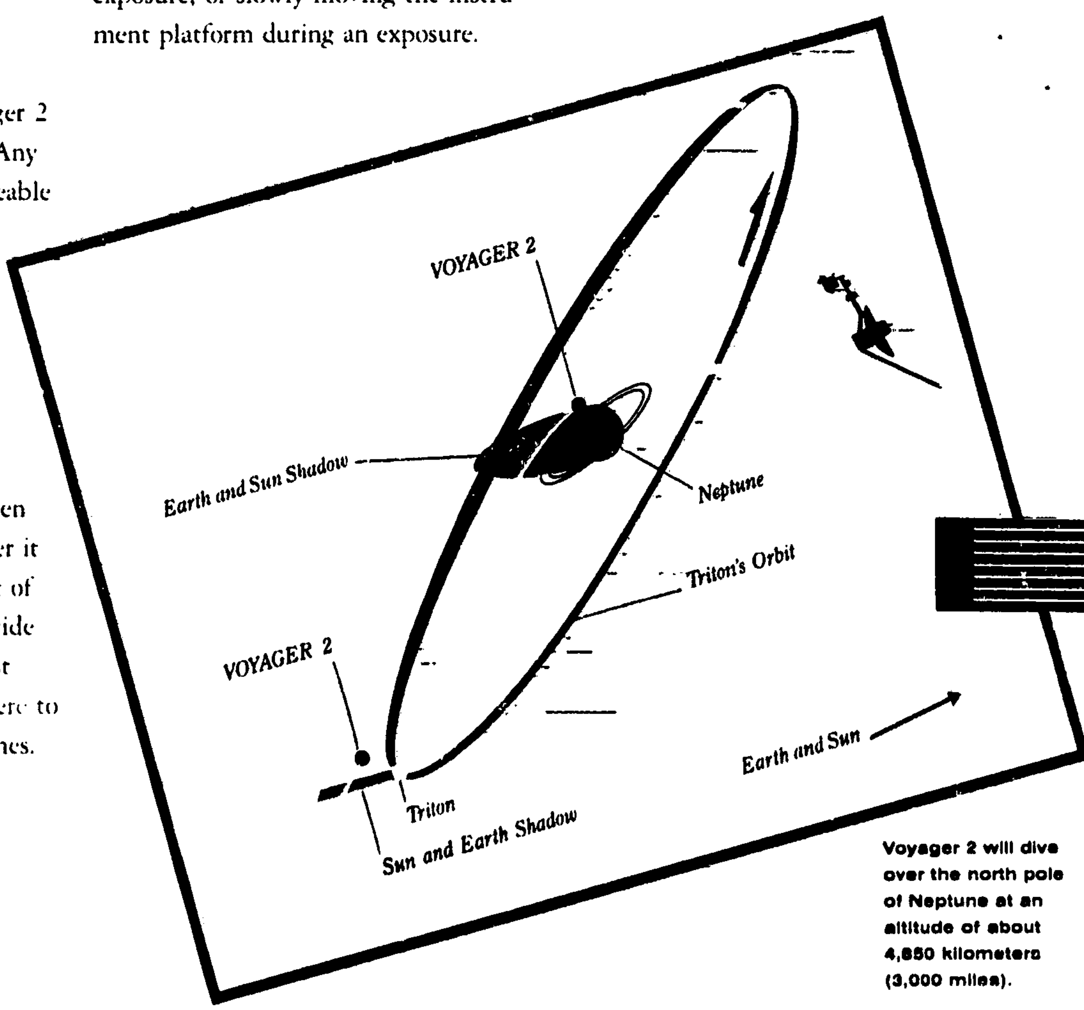


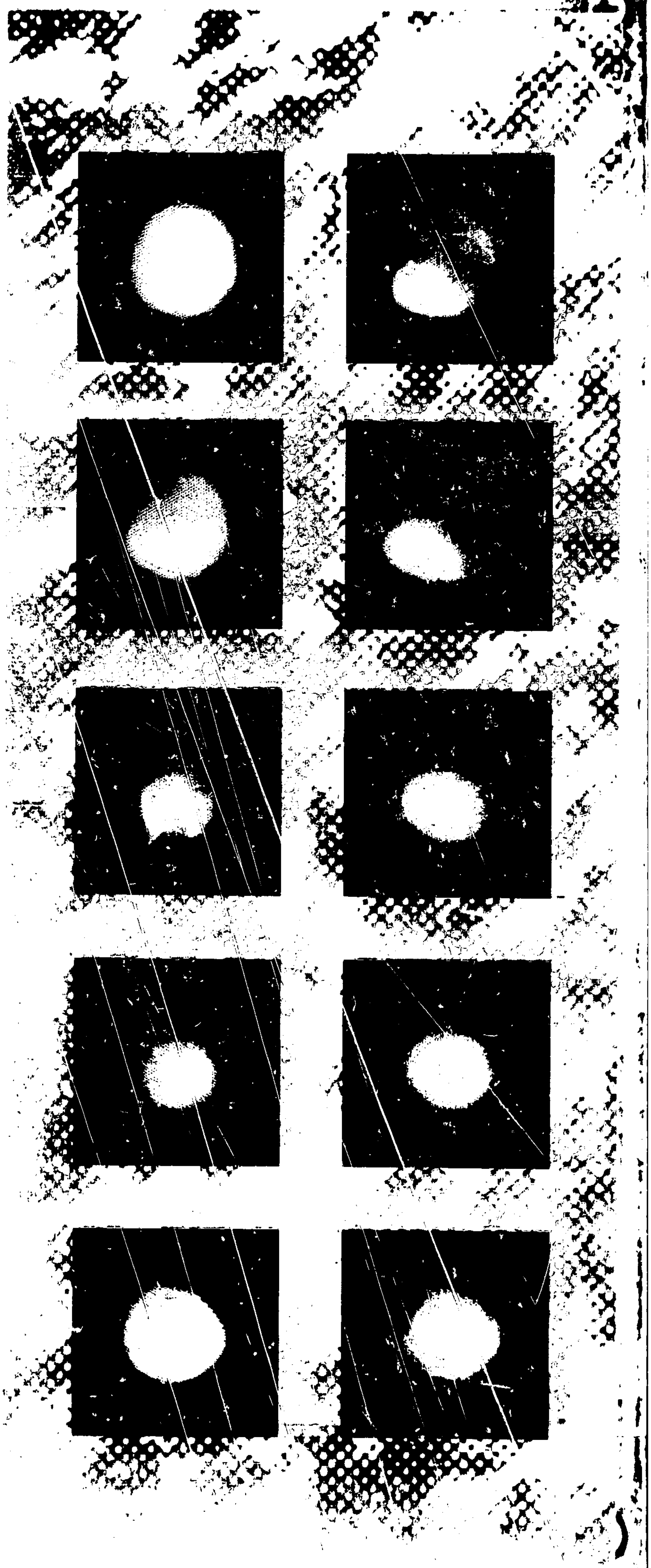
Image-motion compensation techniques resulted in a dramatic improvement in the resolution obtained of the Uranian moon Miranda.



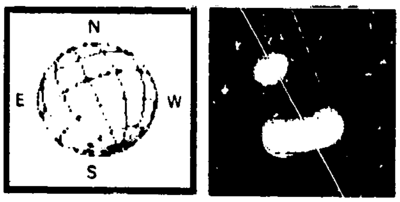
Voyager 2 will dive over the north pole of Neptune at an altitude of about 4,850 kilometers (3,000 miles).

Voyager 2 is also being steadied as an observing platform. Normally, the space craft is steadied by short (10-millisecond) bursts of hydrazine propellant from its attitude control thrusters. For the Uranus encounter, flight engineers reduced the thruster bursts to 5 milliseconds, and for Neptune the bursts will be shortened to 4 milliseconds, reducing the spacecraft rotational rates by an additional 20 percent.

A third effort to gain the best images from Neptune involves changes in software on the ground and on the spacecraft. Previously, exposures longer than 15 seconds had to be recorded on the spacecraft's digital tape recorder for later playback to Earth. While exposures at Neptune will typically be 15 seconds, the software changes will allow the spacecraft to obtain nonrecorded images with longer exposures, greatly increasing imaging flexibility in the dim Neptune environment.



Ground-based images of Neptune, taken over a 5½-hour period in July 1988 provide evidence of cloud structure and a haze at the north pole. Left: Images taken at 6190 angstroms (same wavelength as Voyager's wide-angle camera's methane-band filter). Right: Images taken at 8900 angstroms. (Courtesy of H. Hammel, JPL/ Mauna Kea Observatory.)



Clouds on Neptune were seen in ground-based images in 1983. (R. Terrile, JPL, B. Smith, Univ. of Arizona.)

After Neptune, the Voyager spacecraft planetary encounters will be over. Only one planet in the solar system remains unvisited—Pluto—and neither of the Voyagers can change its course to visit that planet.

But the Voyager missions will continue as the two spacecraft hurtle onward through space, one above the ecliptic and one below, searching for the edge of the heliosphere—the heliopause, which is the outer boundary of the Sun's energy influence. Crossing the heliopause, perhaps early in the next century, they will enter true interstellar space. These spacecraft may give us the first direct measurements of the environment outside our solar system, including interstellar magnetic fields and charged particles.

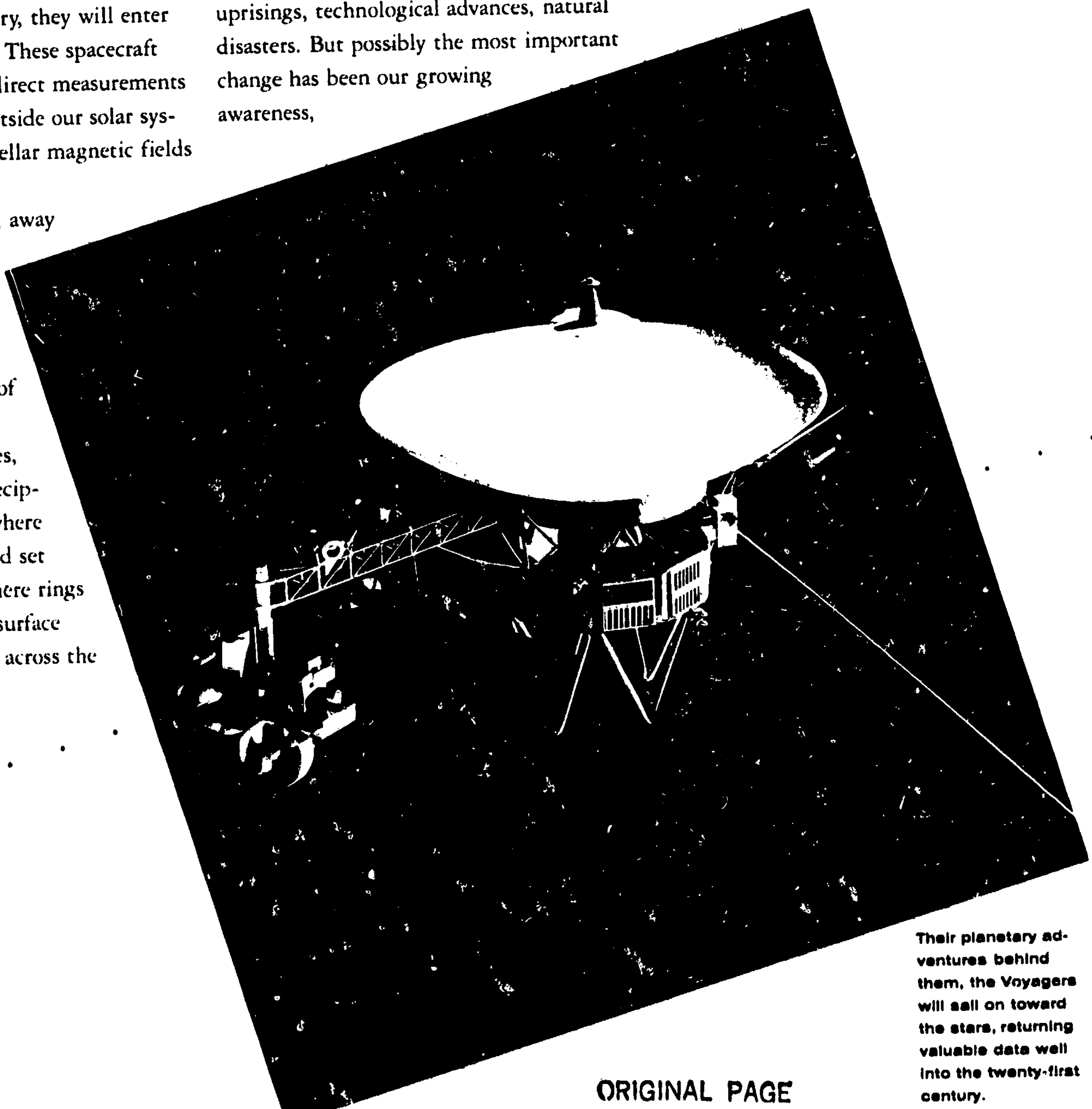
Go out some night, away from the lights. Gaze up at the canopy of stars. Among them you will see other worlds: worlds of freezing temperatures and crushing pressures, noxious gases and precipitous cliffs. Worlds where several moons rise and set every day. Worlds where rings cast shadows on the surface and cut an icy swath across the sky. Worlds where superbolts of lightning slice the air, and auroras light up the horizon for thousands of miles. Worlds vastly different from our own.

And yet, our planet has much in common with these others. We receive energy from the same Sun. Physical processes—gravity, chemistry, and geology—obey the same laws. But in comparison with these other worlds, Earth is unique: it supports life.

Much has happened on Earth since the Voyagers left—social change, political uprisings, technological advances, natural disasters. But possibly the most important change has been our growing awareness, partially brought about by the breathtaking views of other worlds sent back by the Voyagers, of Earth as a planet, and a very fragile one.

Perhaps this is the legacy of Voyager, so well expressed by the poet T.S. Eliot:

We shall not cease from exploration
And the end of all our exploring
Will be to arrive where we started
And know the place for the first time.



Their planetary adventures behind them, the Voyagers will sail on toward the stars, returning valuable data well into the twenty-first century.

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