Voyager at Uranus: 1986

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Uranus, the seventh planet from the Sun, is so far from Earth, at a distance of nearly two billion miles, that its discovery in 1781 doubled the size of the known solar system.

The third largest of the planets, Uranus is circled by at least nine charcoal-black rings. Unlike any of the other planets except Pluto, Uranus lies on its side. It may have been at an early stage of formation when it was tipped off its original axis in a violent collision with another body.

As Uranus travels the solar system in this unusual position, one pole remains in sunlight for 42 years while the other is dark. Then, for the next 42 years, the situation is reversed. Currently, its sunlit southern pole is framed at the center of the nine rings, like a giant bull's-eye.

The Voyager 2 spacecraft is now headed toward that distant target, after having completed highly successful investigations of Jupiter in 1979 and Saturn in 1981. Voyager will fly past Uranus at 10 a.m. (PST) on January 24, 1986, passing within 107,000 kilometers (64,500 miles) of the planet's cloud-tops. The spacecraft's trajectory, which will eventually take it out of the solar system, offers the only opportunity in the foreseeable future to conduct closeup studies of Uranus, and later, Neptune.

Thus, Uranus will be the third planet encountered by the spacecraft in the first nine years of its three-billion-mile path looping through and then out of the solar system.

Because of its remoteness, Uranus is difficult to study, but a surprising amount has been learned through painstaking studies from observatories on Earth. Even so, information about the planet is sparse when compared to what is known of planets nearer to Earth.

The Voyager encounter will be the most intensive study of Uranus ever undertaken, with initial observations beginning November 4, 1985. The spacecraft's last look at the planet will occur on February 25, 1986. Many of the highest-priority measurements will be obtained on January 24, 1986, during the six hours it takes Voyager to sweep through the Uranian system. In half a day, scientists will gain more knowledge of the planet and its moons, strange ring system, and unique magnetic field than has been learned about Uranus in more than 200 years of astronomical study.

Facing page: Uranus and its rings, showing the planet's sunlit southern pole. (Original painting by Don Davis.)

Cover: An artist's concept shows how Uranus and its black rings might look from the vicinity of one of the planet's five moons. (Painting by Ludvek Pesek, © National Geographic Society.)

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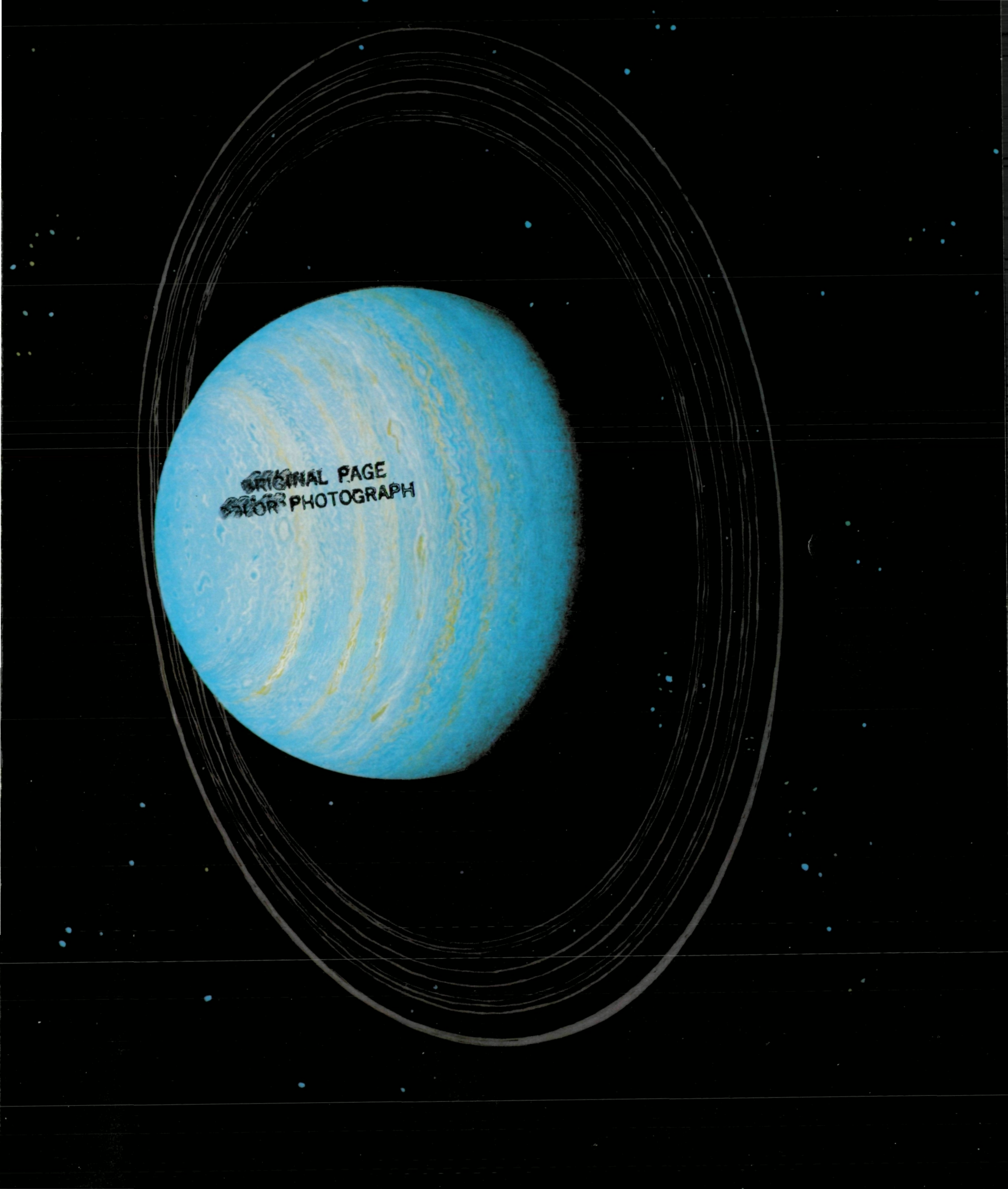

The Voyager Mission

Voyagers 1 and 2 were launched in August and September 1977 on trajectories that would take them to Jupiter and Saturn, then deliver each spacecraft to explore different regions of space outside our solar system.

Voyager 1 has completed its planetary encounters and is now climbing through unexplored space on a path upward from the ecliptic plane, the broad disk in which Earth and most of the other planets orbit the Sun. Already farther above the ecliptic plane than any other spacecraft, Voyager 1 is returning valuable information on this uncharted region.

Meanwhile, two more planets have been added to Voyager 2's itinerary. At its Saturn encounter in August 1981, Voyager 2 was deflected and its velocity increased as the spacecraft swung by Saturn and onto a path that would put it at Uranus in January 1986. There, Voyager 2 will respond to the pull of that planet's gravity, and its course will be changed again, this time toward Neptune, which the spacecraft will pass on August 24, 1989. These gravity-assisted trajectory changes, which require passing each planet at a precise point in space and time, are the key to the concept of Voyager 2's grand tour. Given the launch vehicles available in 1977, the Voyagers would have lacked the velocity to fly to Saturn without first flying past and gaining an increase in velocity from Jupiter. Even with a more powerful launch rocket, it would take a spacecraft 30 years to travel a direct path to Uranus. The boost in velocity Voyager 2 received in its swing past Jupiter, for example, was equal to that which it gained from launch.

The gravity-assist technique thus allows Voyager to tour all four of the giant planets in little more than a decade.

Voyager 2's Uranus encounter and Voyager 1's deep-space exploration mission have been retitled the Voyager Uranus/Interstellar Mission.

Uranus

Uranus is one of the giants of the solar system, but even at about 64 times the volume of Earth, the planet is so far away that it can't be seen without powerful binoculars or a telescope. The light that

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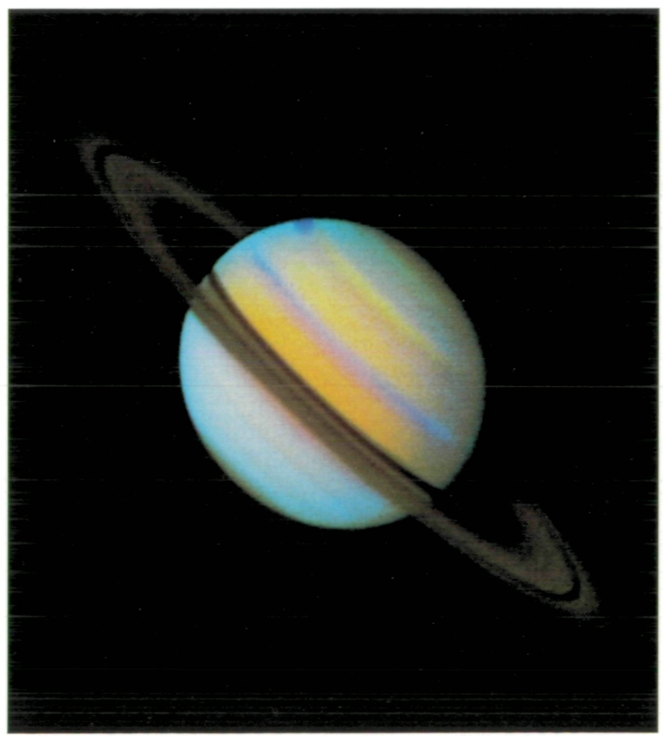

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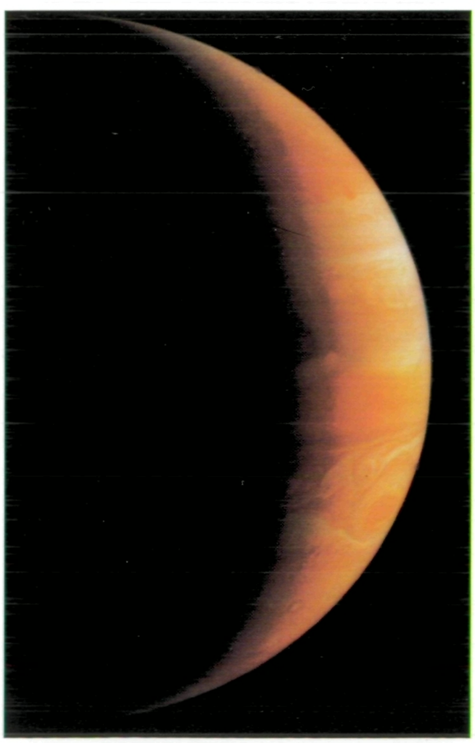

reaches Earth from Uranus is 1,600 times fainter than that received from Jupiter.

Uranus and Neptune are near-twins: their compositions are similar, and they're almost the same size—Uranus is about 51,100 kilometers (31,800 miles) in diameter, and Neptune is about 50,000 kilometers (31,000 miles).

The most distinctive feature of Uranus is its unusual rotational position, tipped over on its axis. Scientists theorize that early in the planet's history, a collision with another planet-size body might have tilted Uranus from a vertical or near-vertical axis to its present orientation.

Earth experiences significant seasonal changes with just a 23½-degree tilt to its axis. Seasons on Uranus, with its 98-degree axial tilt, must be quite extreme. One pole spends half a Uranian year (equivalent to 42 Earth years) in sunlight, while the other pole is in darkness. For the rest of the Uranian year, the polar orientation is reversed.

The length of a Uranian day is uncertain. Direct measurements indicate it is either 16 or 24 hours, while theoretical models based on the planet's rotational properties set the day closer to 16 hours.

Composition

Because of their similar compositions, Jupiter and Saturn are considered by scientists to be one set of twin planets, and Uranus and Neptune another. The bulk of Jupiter and Saturn's composition is hydrogen and helium surrounding

A. Voyager 2 returned more than 15,000 photographs of Jupiter during the spacecraft's July 1979 encounter.

B. This 1981 Voyager 2 photograph was taken with an ultraviolet filter to enhance features in Saturn's atmosphere. It is one of more than 33,000 returned from Saturn by both Voyagers 1 and 2.

C. Voyager 2 will fly through the Uranian system like an arrow through a target. The spacecraft's path will take it close to the innermost moon, Miranda, and the outermost of Uranus' dark rings.

D. The red, roughly elliptical shape in this 1978 computer-processed image shows the irregular structure of Uranus' ring system. The image was constructed from multiple telescope observations of the planet. (Photograph by K. Matthews, G. Neugebauer, and P.D. Nicholson.)

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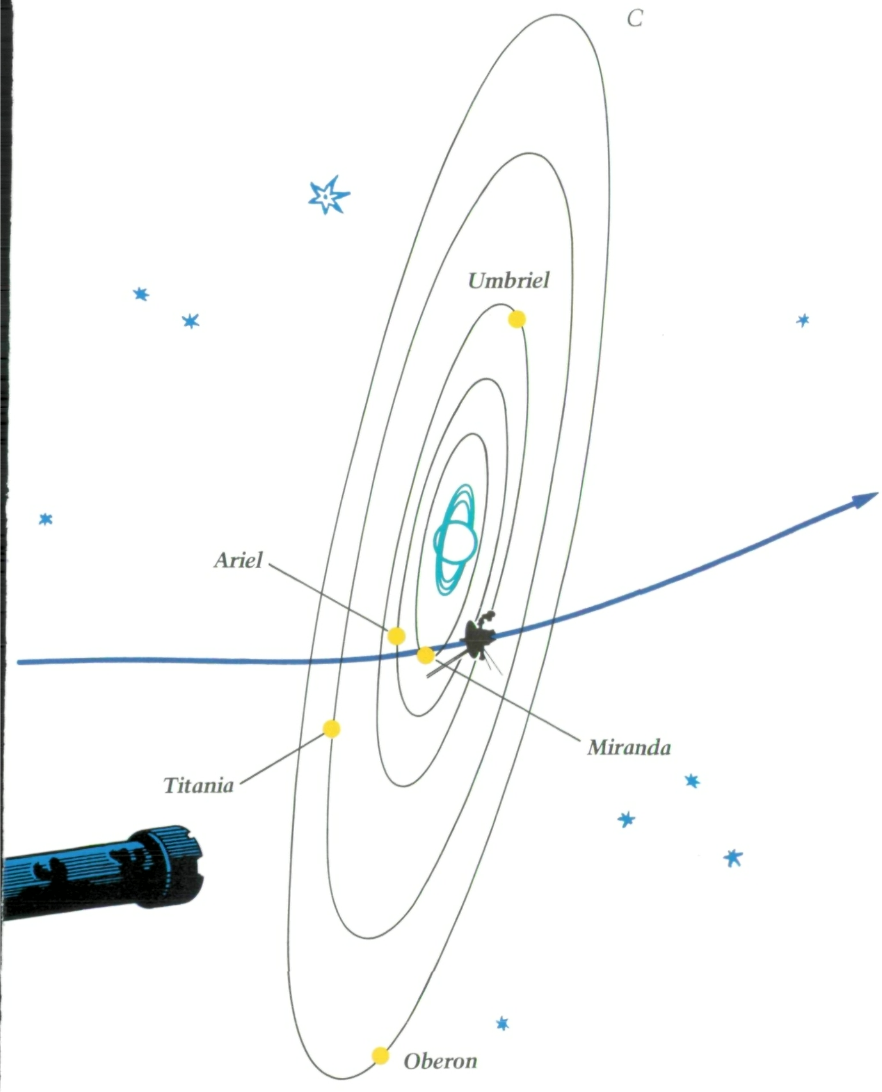

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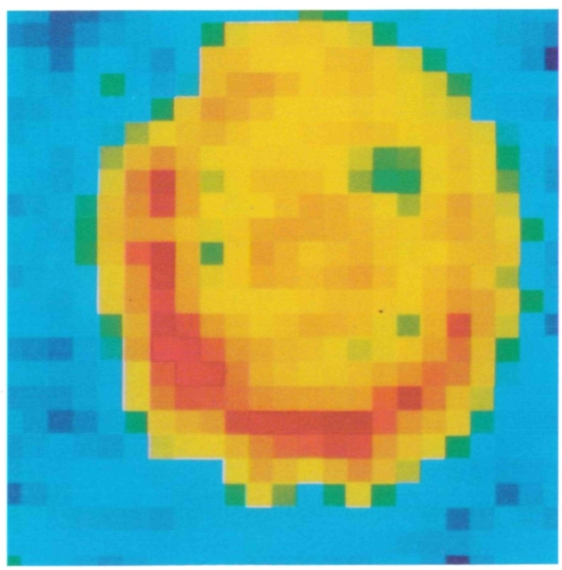


relatively small cores of heavier materials.

By comparison, Uranus and Neptune, while still giants compared to Earth, are each much smaller than Jupiter and Saturn. In fact, the two could represent what Jupiter and Saturn might be like if those planets were stripped of much of their extensive gas envelopes. Uranus and Neptune, nevertheless, possess massive atmospheres consisting mostly of gaseous compounds of hydrogen, carbon, nitrogen, oxygen, and perhaps helium. Each planet may have an ocean of melted ices of methane, ammonia, and water beneath its atmosphere and hazy cloud layer.

Weather

One key to determining what drives the weather system on a planet is found by measuring how much heat is emitted by the planet, versus how much it absorbs from the Sun.

Jupiter, Saturn, and Neptune each have significant internal heat sources—each planet emits more energy than it absorbs from the Sun. Uranus, on the other hand, shares at least one characteristic with Earth in that they both emit little heat of their own making.

Every planet employs some mechanism to distribute the heat it absorbs and the energy it emits. On Earth, sunlight is absorbed mostly at the equator. From there, the oceans and atmosphere distribute the heat north and south to the poles to maintain global temperature equilibrium.

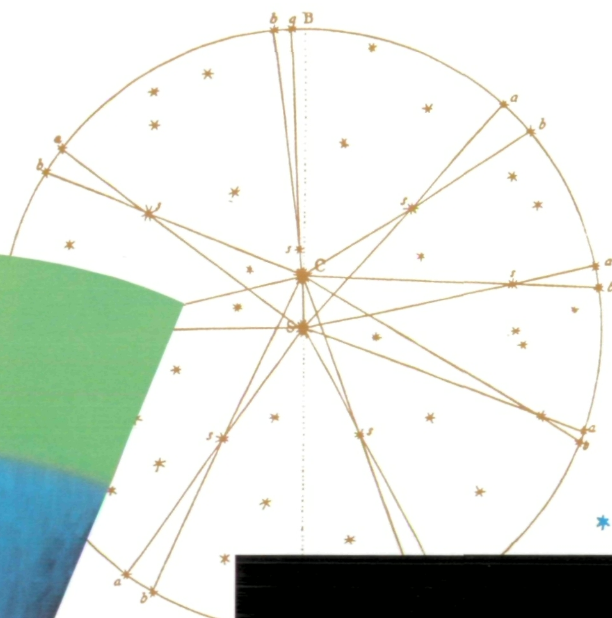
Uranus' southern hemisphere currently absorbs all the sunlight the planet receives, so there may be significant meridional flows—atmospheric motions that cross the latitudes of the planet like the seams in a beachball—carrying heat from one pole to the other.

It is possible that sunlight acts as a kind of thermostat for Uranus, providing enough energy to inhibit the release of internal heat that might otherwise escape.

The Rings

Nine thin, black rings are known to surround Uranus. The outermost ring, called the epsilon ring, reflects only about five percent of the light it receives—it is about as dark as the dark side of Saturn's moon Iapetus. The other eight rings are expected to be equally black.

Three of the rings are very nearly circular. The rest are somewhat eccentric. The epsilon ring is most eccentric, forming an ellipse around



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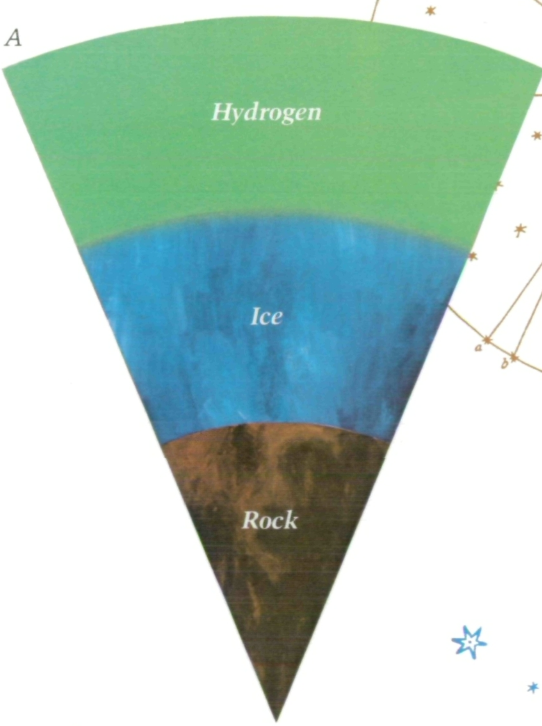

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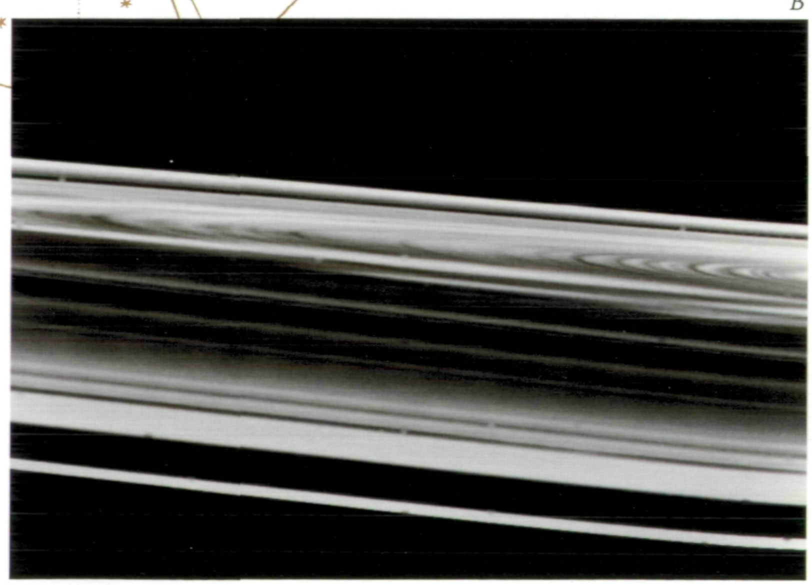


the planet that varies by tens of miles in width.

The ring system was found in 1977 when Uranus passed in front of a bright star, affording astronomers the opportunity to detect the rings as starlight flashed between them.

No one knows if the rings formed with Uranus 4.5 billion years ago, or if they are a more recent development—perhaps the remnants of broken-up moons, meteoroids, or a combination of these.

The darkness of the rings implies that most of the particles lack bright water-ice coatings. The rings could be darkened by the effects of radiation on methane ice, which may be a large component of the ring particles.

The Uranian rings are expected to share some of the physical characteristics unveiled in Saturn's rings by Voyagers 1 and 2. There are likely to be small shepherd moons, like those found at Saturn, which herd ring particles to produce unusually shaped rings. The rings might also exhibit the kinkiness and scalloped edges caused by the shepherd moons, as seen in the Saturnian ring system.

The Moons

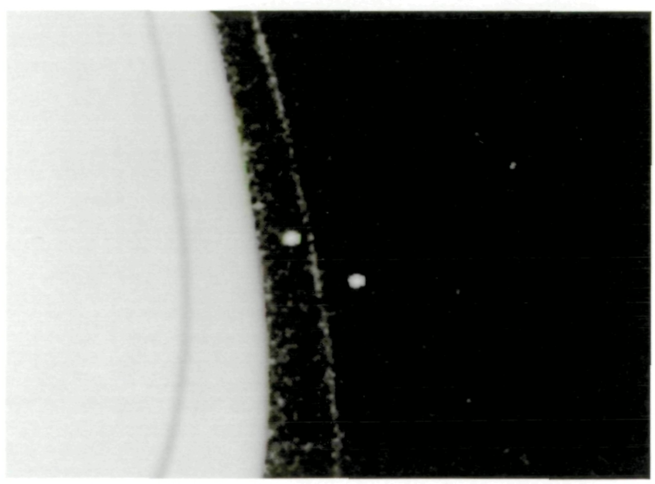
Little is known of the five moons orbiting Uranus; even their sizes and masses are not well determined. The moons could be composed entirely of ice, or they may be a mixture of rock and ice in various combinations, with or without an icy outer coating. But after the remarkable variety of surface features and geologic processes revealed when the Voyagers flew by the moons of Jupiter and Saturn, Voyager scientists are pre-

A. Uranus is believed to consist of a rocky core enveloped by melted ices of methane, ammonia, and water, and topped by a massive atmosphere of gaseous compounds of hydrogen, carbon, nitrogen, oxygen, and perhaps helium.

B. This photograph of Saturn's rings was taken just as Voyager 2 crossed the plane of the rings. Though Uranus' rings are much darker than Saturn's, this view is similar to the view Voyager will have of the Uranian rings at closest approach.

C. Sir William Herschel, discoverer of Uranus, drew these sketches of what he perceived to be rings around the planet. He later discounted the observations.

D. Shepherd moons like these bracketing Saturn's thin F-ring are likely to be found near or within the rings of Uranus.



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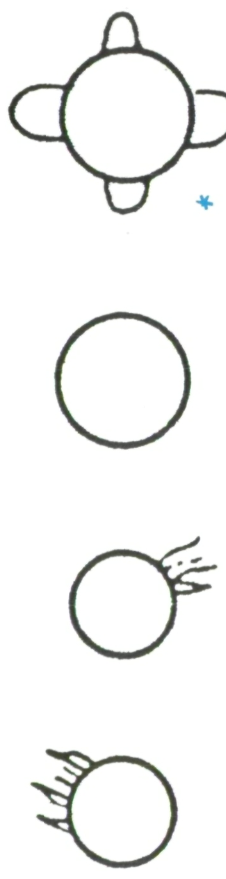

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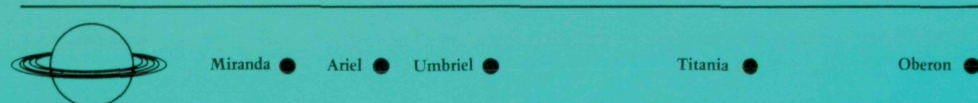
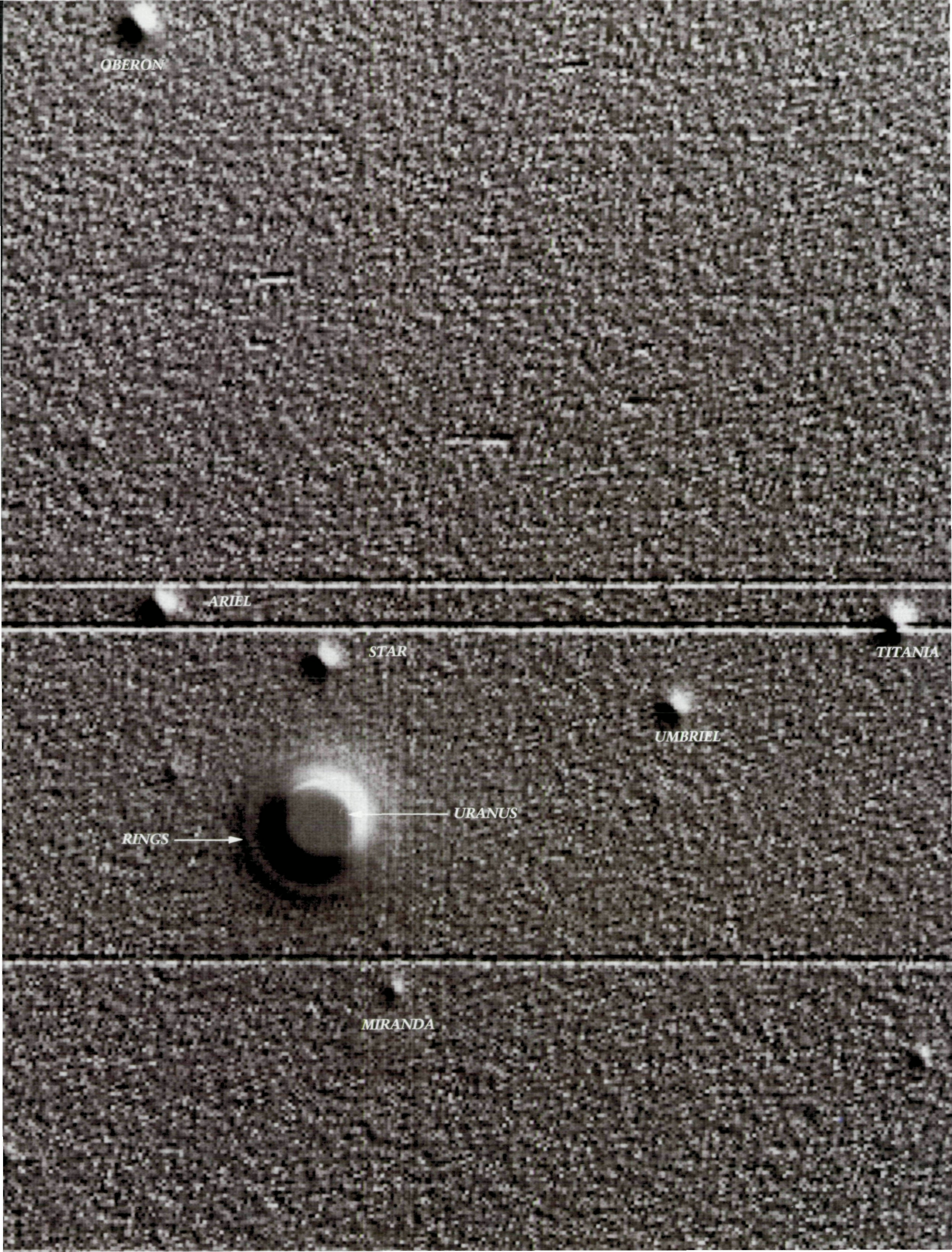
THE URANIAN SATELLITES



Satellite	Diameter		Distance from Planet	
	Kilometers	Miles	Kilometers	Miles
Miranda	500±220	310±135	130,000	80,000
Ariel	1300±130	825± 80	192,000	119,000
Umbriel	1110±100	690± 60	267,000	166,000
Titania	1600±120	995± 75	438,000	272,000
Oberon	1630±140	1010± 85	586,000	364,000


OBERON
ARIEL
STAR
TITANIA
UMBRIEL
URANUS
RINGS
MIRANDA

pared for the unexpected at Uranus.

The moons are about the same size as the intermediate satellites of Saturn, such as Dione or Enceladus. The darkness of their surfaces suggests that they, too, may have been altered by the effects of radiation on methane. They could exhibit tectonic features, such as cracked surfaces or frozen flows of icy magma.

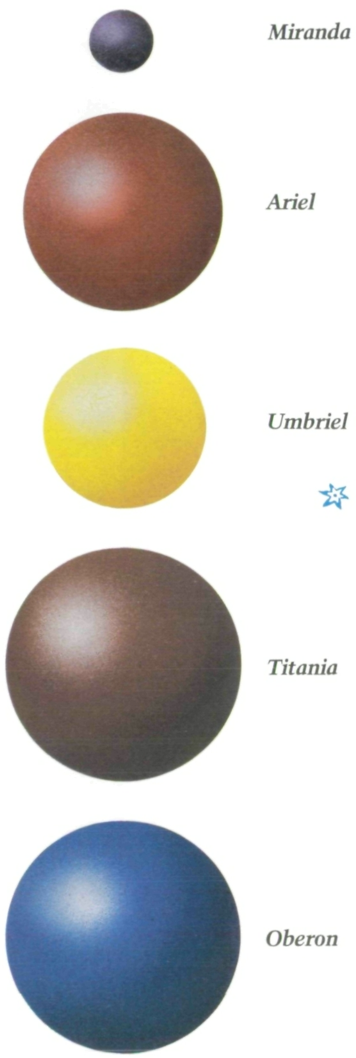
One intriguing suggestion states that some of the moons could have formed from the debris left over after a collision between Uranus and another body. In this scenario, a body one or two times the size of Earth smashed into Uranus, tipped it on its side, and splashed part of the planet's atmosphere into space. The resulting mix of rock and gases would have formed a disk around the planet, out of which the moons might have formed.

The Magnetosphere

Because auroral activity has been reported on Uranus, scientists assume that it must possess a magnetic field. Auroras on Earth and Saturn are caused by the interaction of their magnetic fields with the solar wind, the stream of atomic particles emitted by the Sun.

The magnetic field of Uranus, if one exists, will be unique in the solar system, because of the planet's odd orientation.

A planet's magnetic field is thought to be generated by fluid motion in the planet's interior and rotates with the interior as well. In Uranus' case, the magnetic environment, called the magnetosphere, could extend one million kilometers from the planet. The tail of the magnetic field could extend be-



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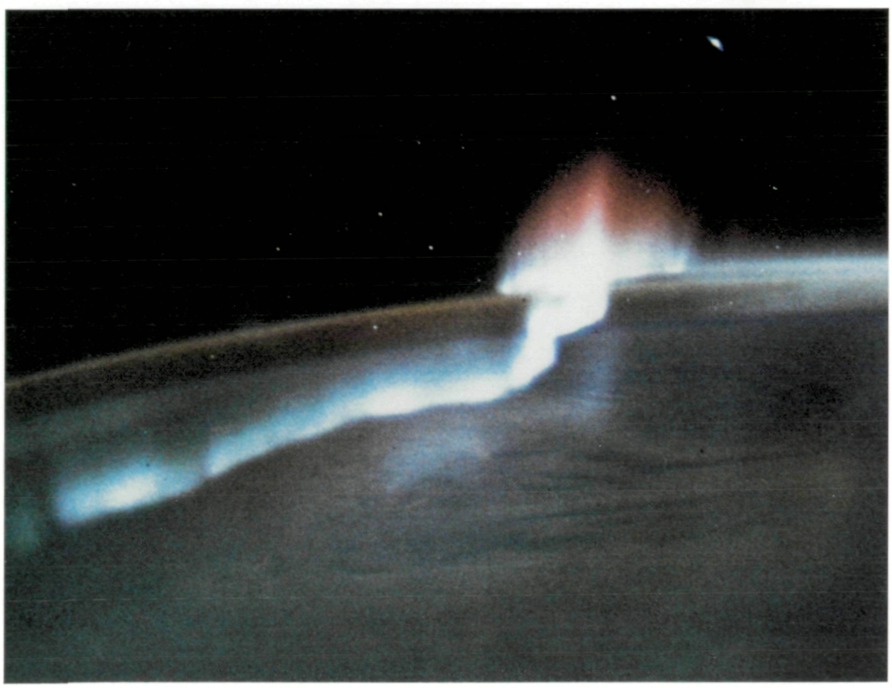


A. This is the first clear photograph of the rings around Uranus. The image was acquired with an electronic camera and a charge-coupled device (CCD) and was computer-processed to create a three-dimensional texture. (Photograph by R.J. Terrile and B.A. Smith.)

B. Auroral activity occurs in the atmosphere of Jupiter and Saturn, as well as on Earth. Voyager 2 will search for auroras in the Uranian atmosphere. This photograph of an aurora in Earth's atmosphere over Australia was taken from NASA's Space Shuttle in May 1985.

Priority Observations During Voyager's Closest Approach

Instrument abbreviations:
IRIS—Infrared Interferometer Spectrometer
PPS—Photopolarimeter
PWS—Plasma Wave
UVS—Ultraviolet Spectrometer
PLS—Plasma Detector
All times are Pacific Standard Time.

Jan. 15
(minus 9 days from closest approach)
Observation: Uranus
Instrument: IRIS
Objective: Measure thermal energy emitted by planet from illuminated hemisphere.

Jan. 23 *(approximately – 1 day)*
Observation: Magnetopause and bowshock crossing
Instrument: Fields and particles instruments
Objective: Search for and characterize edge of magnetic field.

2 p.m. *(– 20 hours)*
Observation: Rings
Instrument: Cameras
Objective: Series of photos for mosaicking.

4 p.m. *(– 18 hours)*
Observation: Umbriel
Instrument: Cameras
Objective: Color photography.

9 p.m. *(– 13 hours)*
Observation: Rings
Instrument: PPS
Objective: Four-hour study of ring characteristics while occulting star (Nunki/Sigma Sagittarii).

Jan. 24
12:48 a.m. *(– 9.2 hours)*
Observation: Oberon
Instrument: Cameras
Objectives: Highest resolution photos.

1:08 a.m. *(– 8.9 hours)*
Observation: Titania
Instrument: Cameras
Objectives: Color photos.

1:40 a.m. *(– 8.3 hours)*
Observation: Sunlit auroral zone
Instrument: UVS
Objective: Highest resolution mosaic of sunside auroral zone.

3:04 a.m. *(– 6.9 hours)*
Observation: Uranus
Instrument: PPS
Objective: Measure solar energy absorbed by Uranus.

3:45 a.m. *(– 6.3 hours)*
Observation: Umbriel
Instrument: Cameras
Objective: Photos at closest approach—365,000 kilometers (226,000 miles).

4:26 a.m. *(– 5.6 hours)*
Observation: Uranus
Instrument: IRIS
Objective: Atmospheric chemical composition at location of radio science occultation point of Earth.

6:16 a.m. *(– 3.7 hours)*
Observation: Titania
Instrument: Cameras
Objective: Highest resolution images.

6:36 a.m. *(– 3.4 hours)*
Observation: Ariel
Instrument: Cameras
Objective: Color photos.

7:01 a.m. *(– 3 hours)*
Observation: Miranda
Instrument: Cameras
Objective: Color photos.

7:14 a.m. *(– 2.8 hours)*
Observation: Uranus
Instrument: PPS
Objective: Measure solar energy absorbed by Uranus.

8:09 a.m. *(– 1.9 hours)*
Observation: Ariel
Instrument: Cameras
Objective: Highest resolution photos.

8:37 a.m. *(– 1.4 hours)*
Observation: Miranda
Instrument: Cameras
Objective: Highest resolution photos.

8:54 a.m. *(– 1.1 hours)*
Observation: Miranda
Instrument: Radio
Objective: Determine Miranda's mass.

9:08 a.m. *(– 0.9 hours)*
Observation: Rings
Instrument: Cameras
Objective: Search for moons embedded in rings at ring-plane crossing.

9:15 a.m. *(– 0.7 hours)*
Observation: Rings
Instrument: PWS
Objective: Ring crossing: search for ring particles near Miranda's orbit.
also:
Observation: Magnetic equatorial plane crossing
Instrument: Fields and particles instruments
Objective: Observe expected maximum in magnetic field, plasma torus, and trapped radiation.

9:18 a.m. *(– 0.7 hours)*
Observation: Uranus
Instrument: UVS
Objective: Study composition of sunlit polar atmosphere while focusing on star Algenib (Gamma Pegasi).

9:38 a.m. *(– 0.4 hours)*
Observation: Uranus
Instrument: PPS
Objective: Measure solar energy absorbed by Uranus.

10 A.M. PST, JANUARY 24, 1986: URANUS CLOSEST APPROACH—
107,000 kilometers (66,000 miles)

10:14 a.m.
(+ 0.2 hours after closest approach)
Observation: Uranus
Instrument: UVS
Objective: Study composition of dark polar atmosphere while occulting star Algenib (Gamma Pegasi).

10:26 a.m. *(+0.4 hours)*
Observation: Rings
Instrument: PPS
Objective: Study of ring characteristics while occulting Algol (Beta Persei).

11:22 a.m. *(+1.4 hours)*
Observation: Rings
Instrument: PPS
Objective: Ring occultation of Beta Persei.

11:44 a.m. *(+1.7 hours)*
Observation: Rings
Instrument: Radio
Objective: Occultation of radio signal by rings.

12:06 p.m. *(+2.1 hours)*
Observation: Uranus
Instrument: UVS
Objective: Atmospheric studies while occulting Sun.

12:36 p.m. *(+2.6 hours)*
Observation: Uranus
Instrument: Radio
Objective: Atmospheric studies; occultation of radio signal by planet.

2:35 p.m. *(+4.6 hours)*
Observation: Rings
Instrument: Radio
Objective: Occultation of radio signal by rings.

7:42 p.m. *(+9.7 hours)*
Observation: Auroral zone on dark side of planet.
Instrument: UVS
Objective: Highest resolution mosaic of darkside auroral zone.

9:27 p.m. *(+11.5 hours)*
Observation: Uranus
Instrument: PPS
Objective: Measure solar energy absorbed by Uranus.

Jan. 25
3:55 a.m. *(+17.9 hours)*
Observation: Uranus
Instrument: PPS
Objective: Measure solar energy absorbed by Uranus.

6:00 a.m. *(+20 hours)*
Observation: Rings
Instrument: Cameras
Objective: Series of photos for mosaicking.

Jan. 28
(approximately +4 days)
Observation: Magnetopause
Instrument: Fields and particles experiments
Objective: Measure environment as spacecraft leaves magnetotail.

Feb. 2 *(+9 days)*
Observation: Uranus
Instrument: IRIS
Objective: Measure thermal energy emitted by planet from dark hemisphere.

hind the planet to a much greater distance.

The magnetic field is expected to be roughly aligned with the body's rotational axis. Since Uranus' rotational axis is currently directed toward the Sun, its magnetic field would meet the solar wind nearly pole-on. The magnetic field in the polar region would be funnel-shaped, dipping inward at the pole. This would allow the solar wind to penetrate closer to the planet than would otherwise be possible.

As with other planets, the solar wind would deform the outer regions of the magnetic field to produce, in this case, a long tail extending directly away from the planet's northern pole. The magnetotail may also be twisted into a spiral by the rotation of the planet. Voyager's instruments could detect such a structure if it exists.

There may be energetic particles trapped within the Uranian magnetosphere (like those at Saturn). Such particles could produce the radiation effects that might explain the moderately dark surfaces of the moons as well as the extremely dark rings.

Planning the Uranus Encounter

With the previous Voyager encounters, mission planners enjoyed the relative luxury of sending a spacecraft through planet–satellite systems laid out in a horizontal plane, where close approaches to moons occurred practically one at a time. The voyages through the Jovian and Saturnian systems took place over many days, and the hundreds of measurements and detailed observations carried out at those planets proceeded at a pace that, when compared with what's planned for Uranus, seems almost leisurely.

Because of the unique vertical orientation of the Uranian system, Voyager's view will be dominated by the planet's polar region for weeks before the spacecraft's closest approach. While Uranus will loom progressively larger in Voyager's field of view, the perspective essentially won't change until just hours before closest approach. At that time, the pace will pick up dramatically.

Nearly all the highest resolution observations of the planet, moons,

At Uranus, Voyager 2 will

- ☆ *Determine the rotation rate of the planet.*
- ☆ *Profile the structure (pressure and temperature) of the atmosphere and determine the atmospheric composition at depth.*
- ☆ *Measure how much sunlight is absorbed by the atmosphere, and how much energy, if any, is emitted from the deep interior.*
- ☆ *Map the location of clouds and hazes.*
- ☆ *Measure wind speeds at various latitudes in the sunlit, southern hemisphere.*
- ☆ *Search for and map auroral activity at both poles.*
- ☆ *Listen for planetary radio emissions.*
- ☆ *Determine the size, composition and distribution, and reflective properties of ring particles.*
- ☆ *Profile the location and eccentricities of the rings.*
- ☆ *Search for new rings.*
- ☆ *Look for shepherd satellites.*
- ☆ *Measure the masses of some or all of the moons.*
- ☆ *Obtain the sizes, surface features, and densities of the moons.*
- ☆ *Identify geologic processes that have altered the surfaces of the moons and map surface features.*
- ☆ *Measure the strength, orientation, and rate of rotation of the magnetic field.*
- ☆ *Determine the charged-particle population trapped in the magnetic field.*
- ☆ *Locate the position and character of the bowshock—the environment where the solar wind meets the planet's magnetic field.*
- ☆ *Determine the structure of the magnetotail.*

and rings by instruments on the scan platform will occur in the four hours before and two hours after closest approach to the planet.

Remodeling Voyager in Flight

The fact that Voyager 2 is being flown beyond its original design lifetime intensifies the already challenging Uranus encounter for project engineers and planners.

Both Voyagers, however, have been found to be extremely adaptable over the seven years since the spacecraft were launched. This adaptability has allowed engineers to endow Voyager 2, in particular, with new capabilities even as it flies billions of miles away from the planet where it was designed and assembled.

Voyager 2 has been heavily reprogrammed during its flight, and its six onboard computers have been continually taught newly developed and more expedient methods of processing data. As one Voyager engineer put it: "We're flying a different spacecraft than we launched."

Image Data Compression

Each Voyager sent about 17,000 images of the Jovian system, and, due to the increased distance and lower data rate, about 2,000 fewer of the Saturnian system.

The quality of the radioed data stream decreases with Voyager 2's increasing distance from Earth. By lowering the rate at which the spacecraft transmits data, controllers reduce to an acceptable level the amount of noise that will arrive mixed with the data. This maintains the overall quality of the information received.

While the data rates will be much lower at Uranus, Voyager scientists and engineers have devised a technique to squeeze more than 200 images a day out of the limited data stream expected during the Uranus encounter. This has been made possible by reprogramming

The Australian government has offered its Parkes Radio Observatory 64-meter dish antenna for use during the Voyager Uranus and Neptune encounters. The antenna will greatly enhance the data return during critical phases of the encounters.

two of the six computers on the spacecraft. One computer is devoted to formatting data from the spacecraft engineering subsystems and all the experiments except imaging. The second computer separately compresses and formats all imaging data prior to its transmission to Earth.

Instead of transmitting the full eight bits (containing 256 gray levels) for each picture element, or pixel, only the difference between the brightness of successive pixels is transmitted. The result of this image data compression will be at least a 60 percent reduction in the number of bits needed per image.

Computer-processing of the imaging data at JPL will restore the correct brightness to each pixel to produce complete black-and-white and color images.

At Uranus, the minimum amount of time a picture will take up in Voyager's radioed data stream will be four minutes, compared to 2 minutes, 24 seconds at Saturn and 48 seconds at Jupiter. Without the new image data compression technique, each picture would take up nearly 13 minutes in the data stream, severely limiting the number of images that could be returned.

High-Speed, Closeup Photography

Voyager 2 will be hurtling past Uranus and its moons at a speed of more than 40,000 miles an hour. This velocity poses a problem for the cameras on board, not unlike the problem encountered by a photographer inside a moving vehicle trying to photograph the passing scenery: distant objects remain in focus, but to get a still photo of a nearby object, the camera has to move while the shutter is open to compensate for the motion of the vehicle.

The moons of Uranus have inherently dark surfaces, and light levels in that region of the solar system are four times lower than at Saturn. These factors, coupled with the high speed and close approaches to the Uranian moons, means that, to get clear pictures, Voyager's cameras have to track their targets with their shutters open.

Called image-motion compensation, this technique involves rotating the entire spacecraft under the control of the computer that keeps the spacecraft stable in space. Normally, the computer would interpret such movement as being outside prescribed boundaries and would take action to stop the rotation. The computer, however, has been reprogrammed to interpret

The Voyager Spacecraft

Voyagers 1 and 2 are the most sophisticated robotic spacecraft ever to have flown. Unlike earlier spacecraft, they are programmed to make independent decisions that safeguard both the spacecraft and its ability to communicate with Earth.

The information the Voyagers returned from Jupiter and Saturn resulted in at least a tenfold increase in our knowledge of those two planets. And there is even more to be learned at their more distant cousins, Uranus and Neptune.

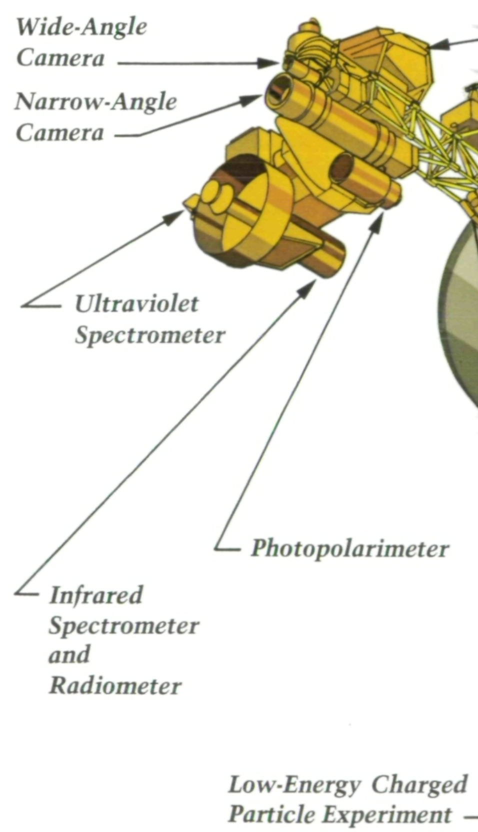
Voyager 2 carries instruments to conduct 11 experiments. Among them are television cameras, infrared and ultraviolet detectors, and a communications system that doubles as a radio experiment. Three sets of twin computers control the spacecraft's stability in space and govern both prescribed and autonomous actions.

All of Voyager 2's instruments are currently operable, although aging components in two instruments may limit the spacecraft's ability to measure the heat radiating from the planet and the amount of sunlight reflected from it.

Voyager 2 has experienced only two major spacecraft problems since launch. The first was a failure of the primary radio system and a loss of automatic frequency tuning in the back-up radio receiver. The automatic tuning compensated for changes in radio frequency caused by temperature changes in the receiver and by velocity differences—the Doppler shift—between Earth and the spacecraft. The loss of that tuning capability has been overcome through long-term monitoring of the receiver under a variety of conditions and through new techniques that allow engineers to predict relative velocities and transmit commands at the precise frequency that can be heard by Voyager 2.

The second problem occurred as the spacecraft swung past Saturn. The movable instrument platform jammed in one of its two axes, preventing pointing of the mounted instruments. Engineers later determined that the jamming was caused by a loss of lubricant and the consequent damage to a bearing in the high-speed gear train, which occurred after repeated high-speed movement of the platform during the busy Saturn encounter.

The platform began moving again, however, when commands were sent two days later. After extensive testing and analysis, Voyager engineers have determined that slow-rate pointing of the platform can be safely accomplished during the Uranus encounter. A prohibition against moving the platform at a high rate will help ensure that the platform will be fully usable when the spacecraft reaches Neptune.



this kind of slow turn as if it were no turn at all, allowing the spacecraft cameras to track their targets without interruption.

This strategy was used successfully at Saturn's moon Rhea, and will be used during the closest approaches to all the Uranian moons.

Long-Distance Communications

Increased distances between the spacecraft and tracking stations on Earth require innovative telecommunications techniques. At Jupiter, data rates of 115,200 bits per second were possible; at Saturn, the rate had dropped to 44,800 bits per second. At Uranus, the spacecraft signal will be considerably weaker. But the same signal, received at two or more antennas at each of NASA's three Deep Space Network stations, will be combined using a technique called arraying. This technique reinforces the strength of the received signals, allowing data rates of up to 21,600 bits per second. The Australian government has also offered its Parkes Radio Observatory 64-meter antenna to be specially instrumented and used during critical phases of the Uranus and Neptune encounters.

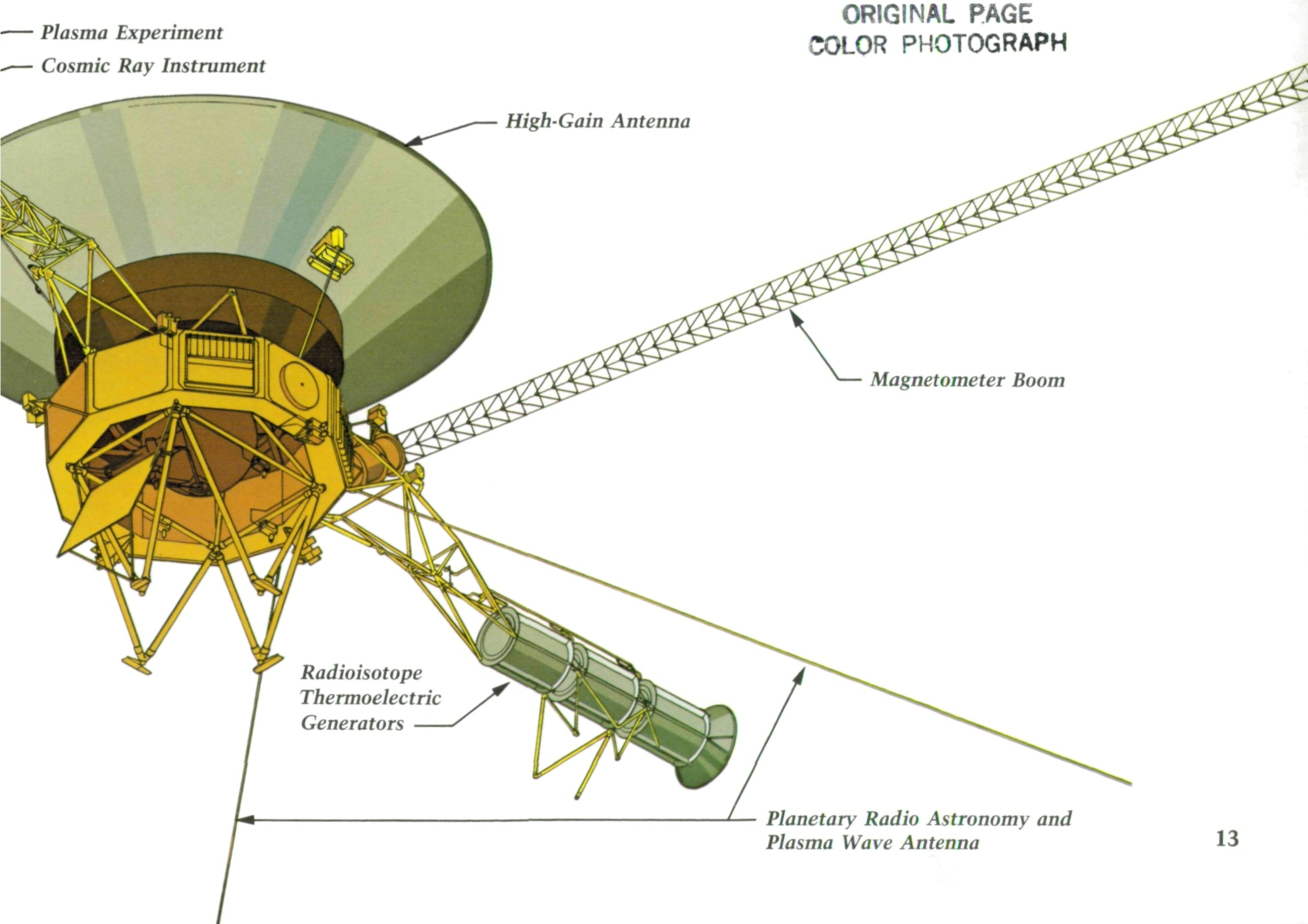
William Herschel and the Discovery of Uranus

A professional interest in musical theory, which broadened to encompass a general study of mathematics, preceded Sir William Herschel's passionate interest in astronomy and led to his discovery of the seventh planet.

He was born Frederich Wilhelm Herschel in Hanover in 1738. His father, a bandmaster in the Hanoverian Guards, encouraged him toward a musical career, and Herschel joined the Hanoverian Guards as a musician in his mid-teens. He moved to England in his early twenties after service in the Seven Years' War. With the goal of becoming a composer, he traveled throughout England working as a freelance musician, music copier, and organist. In 1766, Herschel won appointment as the organist for the new Octagon Chapel in Bath. He was later named director of public concerts for the city.

Herschel read widely on the subjects of harmonics, mathematics, and philosophy. Historians believe the first book he read on astronomy was James Ferguson's *Astronomy Explained Upon Sir Isaac Newton's Principles, and Made Easy to Those Who Have Not Studied Mathematics.*

By his late thirties, his dabbling in astronomy had become a more consuming hobby. He put rudi-



mentary telescopes together from scraps and used parts. The more of the sky he saw, the more he wanted to see. By late 1773, when he couldn't afford to buy the most powerful telescope available, he determined to build his own.

Herschel and his brother Alexander and sister Caroline, also musicians, shared a house in Bath. Building William's telescopes became a family affair.

Alexander helped with the construction. "It was to my sorrow," wrote Caroline in her memoirs, "that I saw almost every room turned into a workshop . . . Alex putting up a huge turning machine in a bedroom for turning patterns, grinding glasses and turning eyepieces."

But Caroline, who would also become a talented astronomer, pitched in as well, even feeding Herschel his meals while he spent hours grinding or polishing by hand a metal speculum, or reflector, for his telescope.

With the best of his telescopes (a 7-foot focal-length instrument with a 6.2-inch reflector), he began what he called "reviews of the heavens" from his garden. Over months of observations, he believed he'd spotted forests of trees on the moon and noted them in his meticulously kept log. He spent many of his observing hours studying double stars and decided to study generally the distribution of the stars and to try to calculate their distances.

While studying stars in the constellation Gemini the night of March 13, 1781, he found a disk-like object moving slowly across the starfield. He believed it to be a comet and reported his observation as such to the British Astronomer Royal.

Within days, however, the object's orbit was calculated as one no comet would likely follow. In addition, it was so distant that, if it had been a comet, it would have been too small to be seen with the instruments of the day.

News of the sighting spread quickly throughout the scientific community. Astronomers and mathematicians across Europe computed the object's approximate size and orbit and, by May 1781, concluded that 42-year-old amateur astronomer William Herschel of Bath had discovered a new planet as far beyond Saturn as Saturn is from the Sun.

Many names were proposed for

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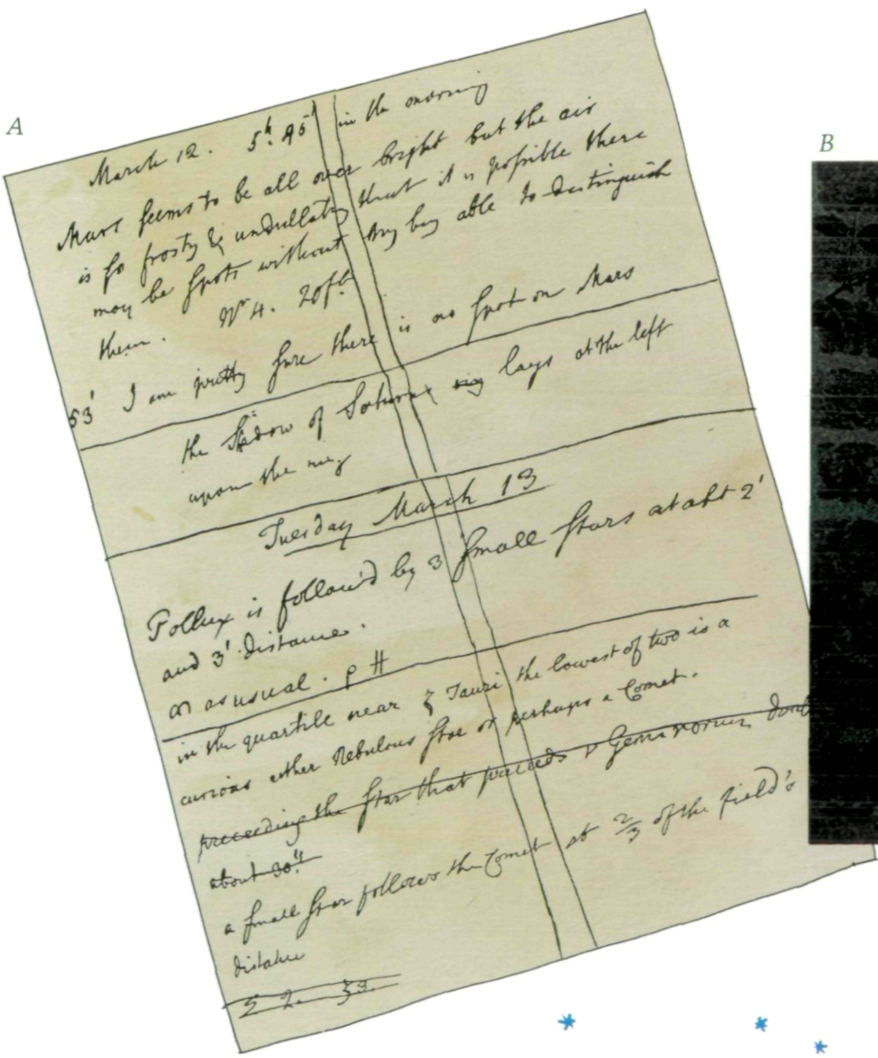

March 12. 5h 45' in the morning
Mars seems to be all over bright but the air is so frosty & undulating that it is possible there may be spots without my being able to distinguish them.
53' I am pretty sure there is no spot on Mars
the shadow of Saturn's ring lays at the left upon the ring
Tuesday March 13
Pollux is followed by 3 small stars at abt 2' and 3' distance.
in the quartile near ζ Tauri the lowest of two is a curious either Nebulous star or perhaps a Comet.
a small star follows the Comet at 2/3 of the field's distance

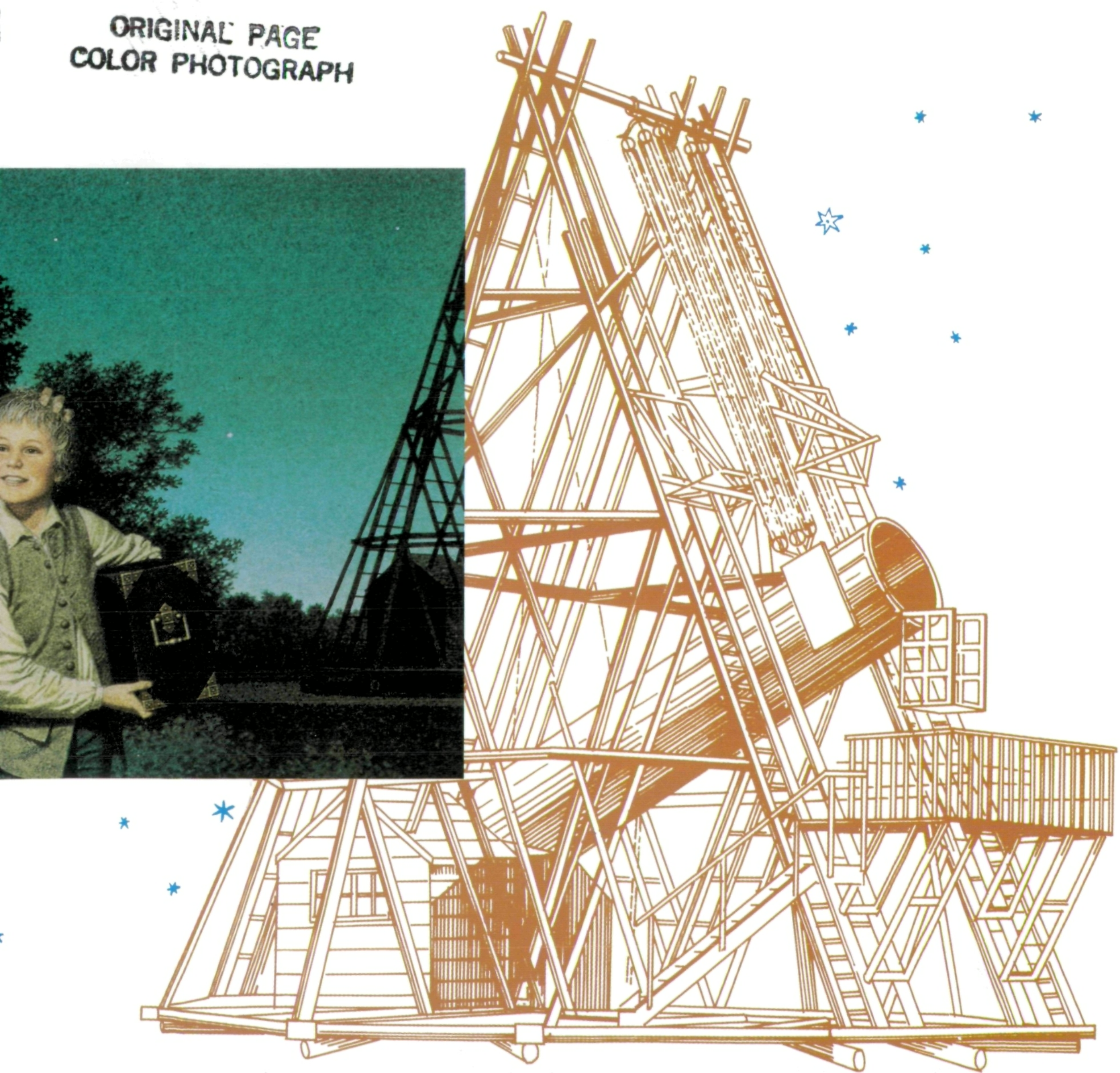
B

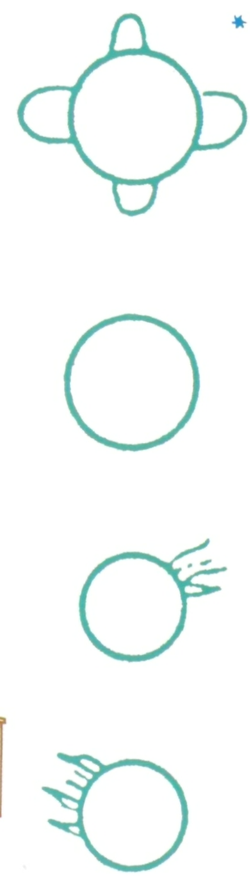
the new body: "Hypercronius" ("above Saturn"), "Minerva" (the Roman goddess of wisdom), and "Herschel" were candidates. Herschel offered "Georgium Sidus" ("The Georgian Planet") to flatter King George III of England and Herschel's native Hanover. (Royal patronage would later support Herschel's work during his distinguished scientific career.) But, astronomy being an international concern and George being an unpopular monarch outside of England and Hanover, variations on his name were vetoed. Astronomers finally agreed upon "Uranus"—personification of the heavens in Greek mythology, son of Gaea (Earth), and, by her, father of Saturn and grandfather to Jupiter.

Herschel, continually building bigger and better telescopes throughout his career, also discovered the Uranian moons Titania and Oberon in 1787. English astronomer William Lassell found Ariel and Umbriel in 1851. Herschel's son, John, named all four. They are the only moons in the solar system not called after figures in Greek and Roman mythology. Instead, they are named for characters in English literature: Oberon and Titania are the king and queen of the fairies in Shakespeare's *A Midsummer Night's Dream*; Ariel and Umbriel appear in Alexander Pope's *Rape of the Lock*; Ariel also appears as a spirit in Shakespeare's *The Tempest*. Miranda, discovered by the late American astronomer Gerald Kuiper in 1948, is named after Prospero's daughter in *The Tempest*.

A. A page from Herschel's notebook of Tuesday, March 13, 1781, describing his observation of what he believed to be a comet. The comet turned out to be Uranus. (Royal Astronomical Society.)

B. Not only did William Herschel become famous as an astronomer, but so did his sister Caroline and his son John, as well. (Painting by Jean-Leon Huens, © National Geographic Society.)





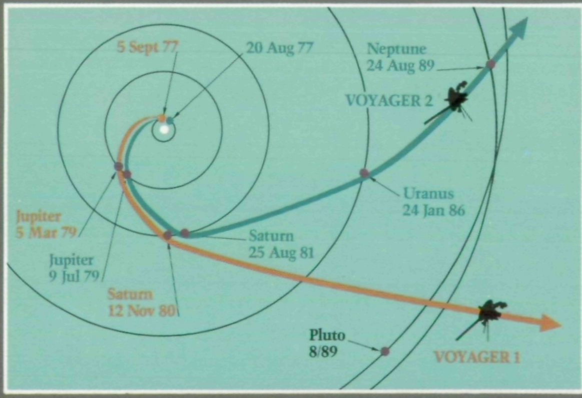
Almost as soon as the Voyager/Uranus encounter ends, scientists and engineers will begin detailed planning of the Voyager's 1989 encounter with Neptune.

As it travels toward its next target, the spacecraft will continue fields and particles experiments in the region between Uranus and Neptune. In addition, engineers will use the three-and-a-half year cruise time to explore new ways to improve Voyager's ability to collect, compress, and return data from Neptune to Earth.

In the late 1990s, both Voyagers are expected to find the heliopause—the boundary where interstellar space begins. Voyager 1 will travel in the direction of the star Rasalhague (Alpha Ophiuchus); Voyager 2 toward Sirius (Alpha Canis Majoris). They will be the first spacecraft to travel through interstellar space.

A. and B. The trajectories of Voyagers 1 and 2 are shown. Voyager 1 embarked on a journey into unexplored space above the plane of the solar system after its Saturn encounter in 1980. Voyager 2, however, pushes on to its Uranus encounter in January 1986, and Neptune in August 1989.

B



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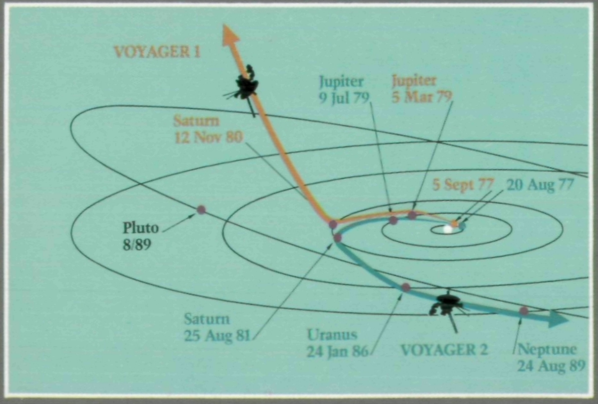

C. On August 25, 1989, Voyager 2 will ▷ come within 20,000 miles of Neptune. (Painting by Don Davis.)

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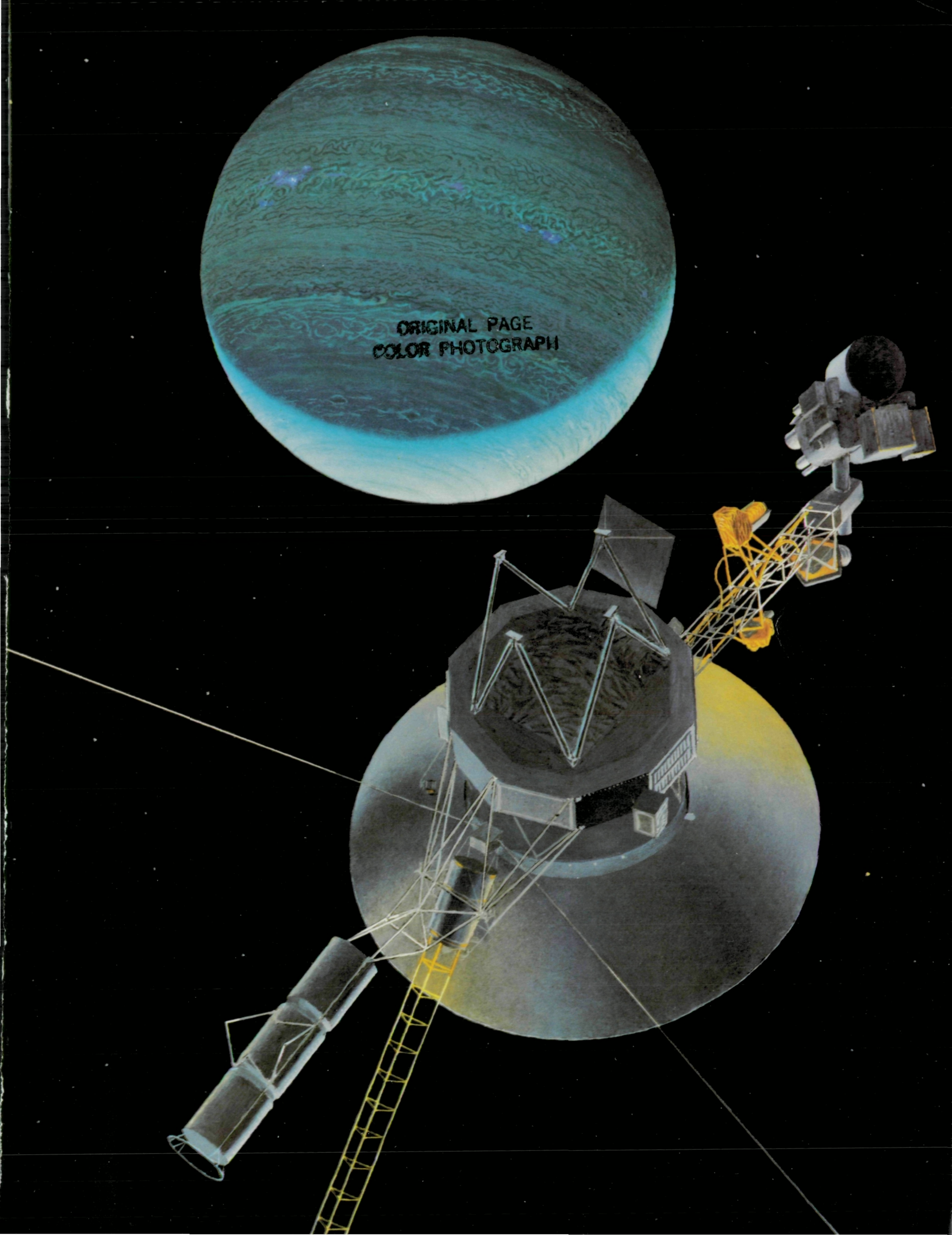
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