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## OREGON TRAIL

THE ITCH TO  
MOVE WEST 147

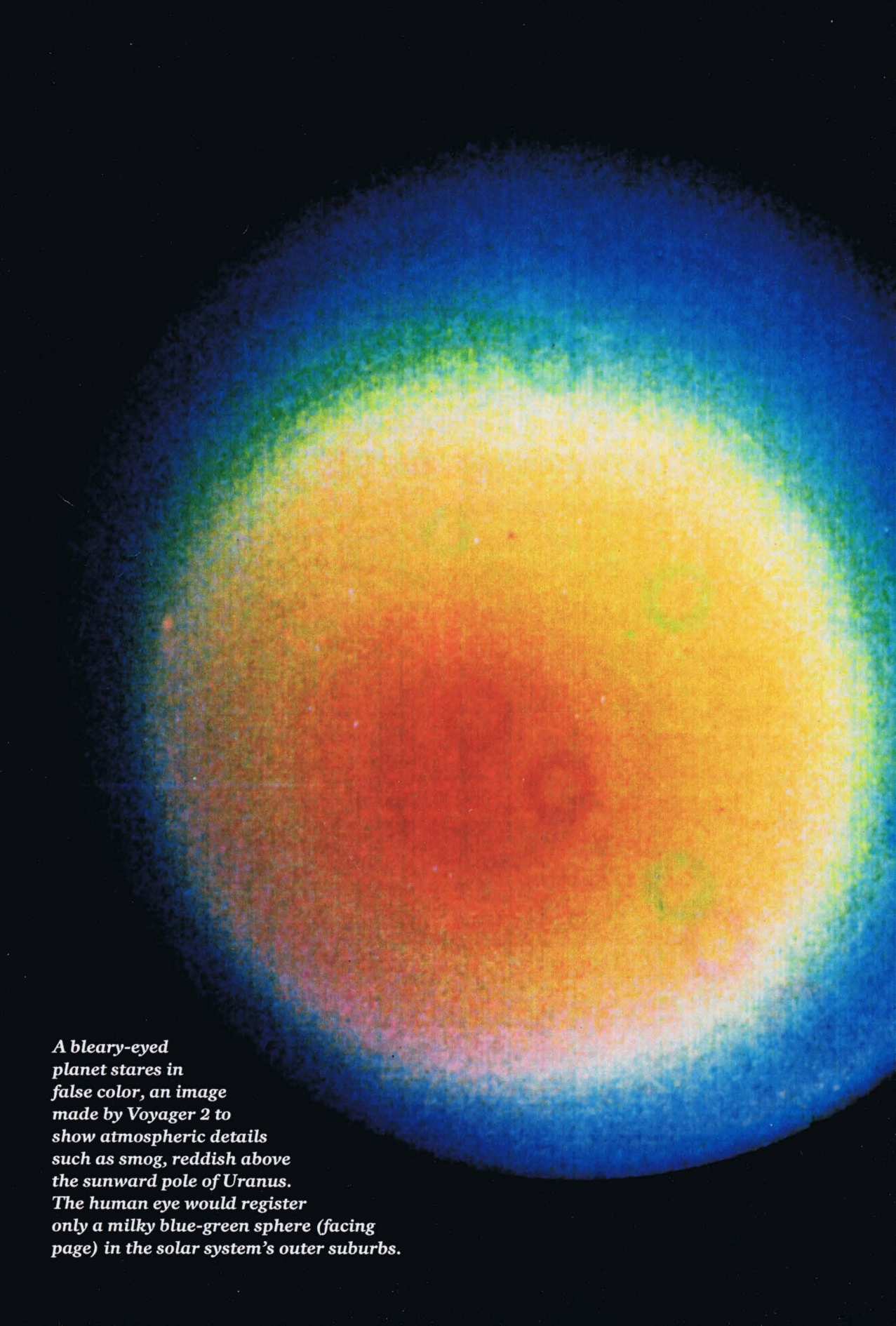
URANUS: VISIT TO  
A DARK PLANET 178

THE QUEST FOR ULYSSES 197

ARGENTINA'S NEW BEGINNING 226

SOVIET-AMERICAN ASSAULT  
ON VICTORY PEAK 256

MARAUDER ANTS 273

A large, circular, false-color image of the planet Uranus. The planet's surface is a mix of colors, with a prominent reddish-orange band across the middle, transitioning to yellow and green towards the top and bottom. The background is a deep, dark blue. The image has a grainy, textured appearance, characteristic of a photograph taken by a spacecraft.

*A bleary-eyed planet stares in false color, an image made by Voyager 2 to show atmospheric details such as smog, reddish above the sunward pole of Uranus. The human eye would register only a milky blue-green sphere (facing page) in the solar system's outer suburbs.*

# Uranus

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## VOYAGER VISITS A DARK PLANET

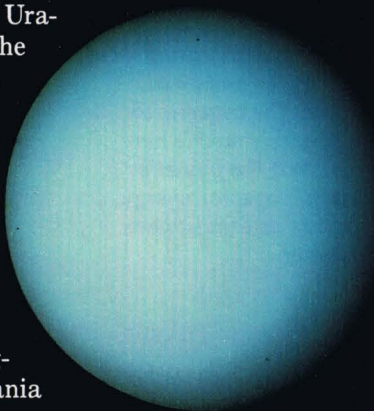
**J**ANUARY 4, 1986. It has been four and a half years since the Voyager 2 spacecraft left the rings of Saturn, more than eight years since it left the launchpad at Cape Canaveral. Now, traveling at 50 times the speed of a pistol bullet, the indomitable spacecraft is approaching Uranus, seventh planet from the sun.

Three billion kilometers away, under dark skies near his house in Hawaii, Brad Smith, head of Voyager's imaging team, muses over this new target. In a few days he will head for the Jet Propulsion Laboratory (JPL) in Pasadena, California, and the cascade of closeup pictures Voyager will send back.

From Earth, Uranus is not visible this evening. Even were it not obscured behind the sun, it is so faint that I would probably need binoculars to observe it. But I have seen Uranus with Smith before, nearly four years earlier, through a large telescope in Chile, as he and Voyager colleague Rich Terrile looked for details to help plan Voyager's flyby.

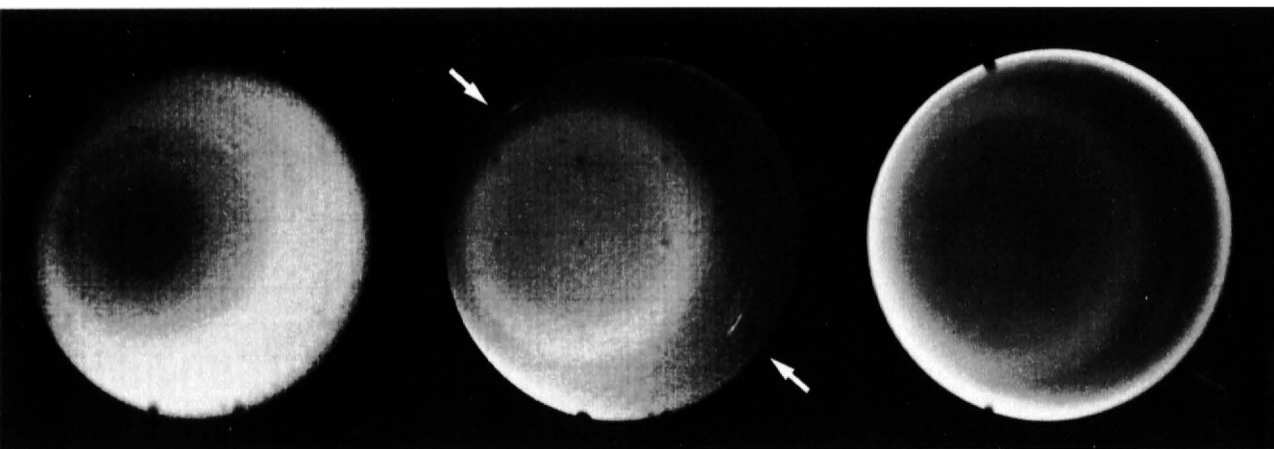
Unlike spectacular Saturn, Uranus does not dazzle through the eyepiece. Its deep, blue-green atmosphere obscures the tumultuous clouds and hot-water ocean that astronomers believe circulate within the planet. In fact, I could have mistaken Uranus for a star were it not for two dots of light around it. Those specks were the two largest of its five known moons: Titania and Oberon.

Titania, Oberon, Umbriel, Ariel, and Miranda. Four of those moons bear Shakespearean names. Umbriel derives from Alexander Pope. Yet Shakespeare, in the words of his sprite Puck, servant to the fairy king Oberon, could have been describing all these moons. "Shadows," Puck called certain spirits, who



By RICK GORE ASSISTANT EDITOR

Photographs by NASA



*Faint banding of the Uranian atmosphere is evident when the planet is viewed through filters of violet, orange, and methane-selective red (above, from left). At right, haze glows as a bright high-altitude corona, while the center view in orange reveals two streaks (arrows), giant cloud tops comparable to thunderheads on Earth.*

*Clouds recorded in time lapse (facing page, top) were seen to move counterclockwise, faster than the planet rotates—behavior exactly contrary to expectations. One question was answered, however. The concentric bands, barely visible here, proved that the planet's rotation, not solar energy, organizes its atmospheric circulation.*

“willfully themselves exile from light, and must for aye consort with black-browed night.”

The Uranian realm is a dark kingdom, so remote from the sun that daylight there approximates a total solar eclipse on Earth. Imagine, suggests Terrile, that the sun is the size of a grapefruit. Then Earth is a pinhead about half a 25-meter pool length away. Jupiter would be a marble three pools out. Uranus would be a mere pea 11 lengths from the sun.

Such distance also makes Uranus unimaginably cold. Since the planets finished accreting from the dusty, gaseous solar nebula more than four billion years ago, temperatures in Uranus's domain probably have not risen much above minus 210°C (−346°F). A space traveler sticking his hand out in that environment would find it instantly freeze-dried.

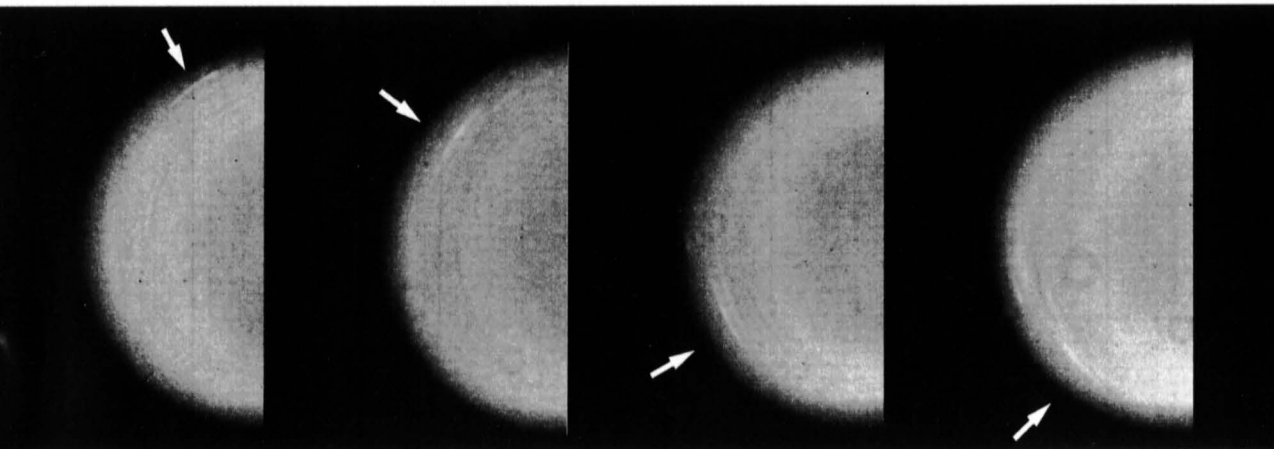
“A planet of unfathomable mystery,” Smith calls this frigid world. For one thing, no one has yet determined how fast the planet rotates, and thus how long its day is. For another, Uranus lies tipped on its side. Astronomers can only guess at what knocked it over; most suspect that an Earth-size object crashed into the planet in its infancy. Like Saturn, Uranus has rings, nine narrow bands. But they are coal black and were not even detected until 1977. What are they made of? The Uranian moons are dark too, the largest but half the size of our moon.

Although Uranus is invisible to us tonight, Smith points out the year's other celestial celebrity—Halley's comet. It is not a bad substitute. For Halley's, like most comets, was probably born near Uranus. In fact, most scientists think Uranus was built from comet cores that collided, then fused together. Voyager would soon reveal how those congealed comets have evolved over the past four and a half billion years.

**J**ANUARY 21. The encounter is under way at JPL. But the pictures of Uranus are strikingly bland. All the powers of JPL's computers can reveal only a few deeply embedded clouds and a faint smoggy haze over the pole that Voyager is approaching.

More intriguing are Voyager's early images of the Uranian moons. From a distance each looks markedly different.

Far darker than its four siblings, Umbriel recalls Pope's own



description of his “hateful gnome,” who flew on “sooty Pinions, a dusky melancholy Spright, as ever sully’d the fair face of Light.” Nearly featureless, Umbriel appears painted over by some dingy material. Yet a bright white ring, nicknamed the “doughnut,” stands out. Could the debris that painted Umbriel have spurting out of the doughnut?

Being able to ask such a question is almost a miracle. Voyager’s sensors were designed for Saturn, where sunlight is four times as bright. Project scientists knew the Uranian darkness would tax their ingenuity: “Taking pictures of the rings and some moons,” explains Rich Terrile, “is like trying to photograph a piece of charcoal against a black backdrop.”

“At Uranus picture exposures needed to be four times as long as at Saturn,” says project manager Dick Laeser. “Since we were going to be flying by at 65,000 kilometers an hour, and didn’t bring along any big strobe lights, our images were going to be badly blurred. So we developed an antismear campaign.”

Voyager’s navigators had to guide the spacecraft within 200 kilometers of a point between the Uranian rings and innermost moon, Miranda. Uranus would thereby gravitationally sling Voyager on toward its 1989 encounter with Neptune. More

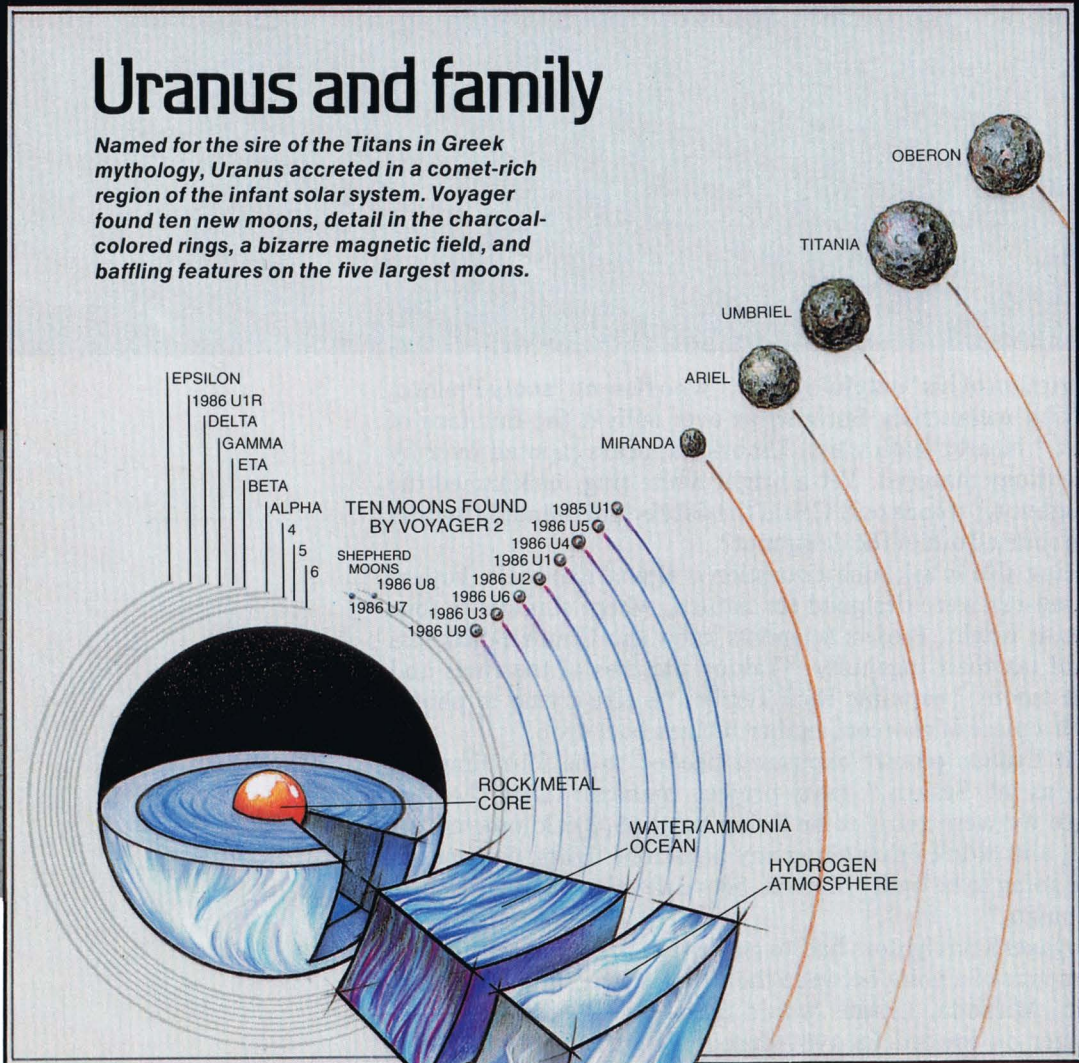


JAMES A. SUGAR, BLACK STAR, WITH GEORGE C. VON KANTOR, NGS STAFF

*“I like it, but I’m not sure whether it works,” comments David Stevenson (left), California Institute of Technology theorist in planetary science, of the idea that the moons of Uranus were created out of debris produced from the collision with an Earth-size body that tilted the planet about 90 degrees some 4.5 billion years ago. Stevenson is currently developing a hypothesis to explain peculiarities of the Uranian magnetic field by examining implications of the planet’s odd orientation.*

# Uranus and family

*Named for the sire of the Titans in Greek mythology, Uranus accreted in a comet-rich region of the infant solar system. Voyager found ten new moons, detail in the charcoal-colored rings, a bizarre magnetic field, and baffling features on the five largest moons.*

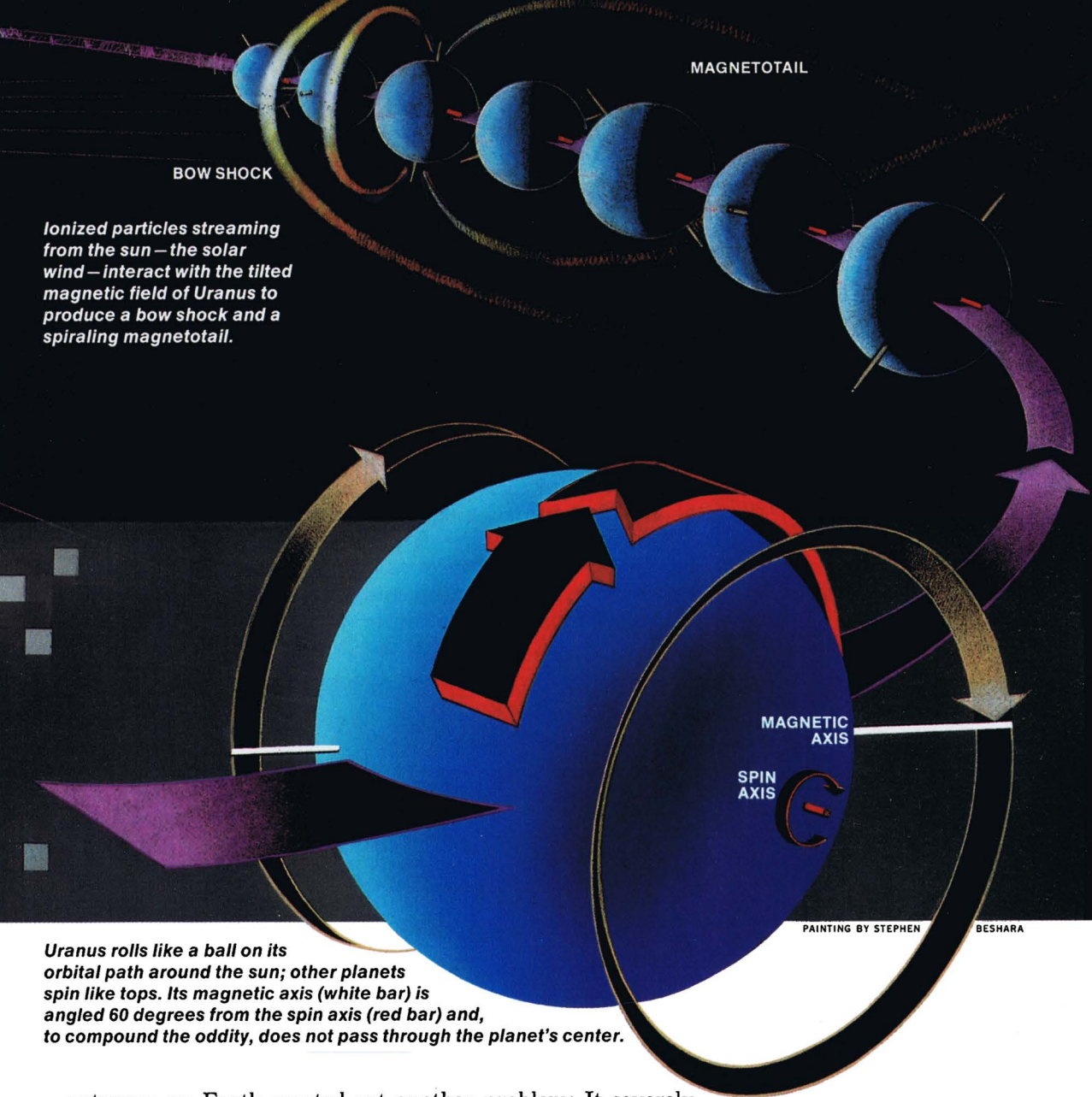


critically, the engineers had to know the precise location of the spacecraft before they sent up the final camera-pointing commands for the Miranda encounter. Otherwise, the cameras might point at black space rather than the moon. That feat is equivalent to William Tell shooting an arrow in Los Angeles and hitting an apple in Manhattan.

Sensors steer the spacecraft by locking onto bright guide stars. Tiny thrusters then routinely fire to keep it pointed on target. But the thrusters cause the spacecraft to wobble slightly, threatening to blur images taken during the long exposures.

To reduce the wobble, the team had to break into the onboard computer program that controls the thrusters—a program that had not been touched since Voyager left Earth. "It was kind of like doing remote open-heart surgery," says Laeser.

The great distance between Voyager and NASA's radio



*Ionized particles streaming from the sun—the solar wind—interact with the tilted magnetic field of Uranus to produce a bow shock and a spiraling magnetotail.*

*Uranus rolls like a ball on its orbital path around the sun; other planets spin like tops. Its magnetic axis (white bar) is angled 60 degrees from the spin axis (red bar) and, to compound the oddity, does not pass through the planet's center.*

antennas on Earth created yet another problem: It severely weakened the radio signals—and thus the amount of data—Voyager could transmit. To cope, JPL's engineers commanded one of Voyager's backup computers to process images onboard, reducing by nearly two-thirds the amount of data needed to be sent back to Earth to create a picture.

Help also came from the Australians, who linked up their 64-meter Parkes radio telescope with NASA antennas near Canberra, creating a much bigger ear with which to hear Voyager.

**J**ANUARY 24. The engineers face their test as Voyager flies within 29,000 kilometers of the little moon Miranda, close enough to reveal features as small as half a kilometer across. Still no one is ready for Miranda.

Scientists were expecting a bland ice ball, little changed since its birth more than four billion years ago. But

*Put Earth in a Uranian orbit—19 times as far from the sun—and our oceans would freeze, while our mainly nitrogen atmosphere would liquefy.*

*Uranus's thick hydrogen atmosphere exerts enormous pressure, heating and perhaps blending with the hot water-and-ammonia ocean that surrounds the planet's rocky, metallic core.*

**Even at light speed,** commands took two hours and 45 minutes to travel from Earth to Voyager, a distance of three billion kilometers (1.8 billion miles). The craft, approaching its bull's-eye at 18 kilometers a second, had no margin for error. For a machine designed to function only as far as Saturn, it performed superbly and "far beyond the warranty period," as one scientist put it.

Miranda is neither stillborn nor monotonous. The moon has been wracked with turmoil. Along one horizon it looks as if fingernails of some angry Titan have gouged out a region of concentric bruises. Cleaving this region are grand canyons as deep as 20 kilometers—the starkest yet seen in the solar system.

The other moons also tantalize and tease (pages 192-3).

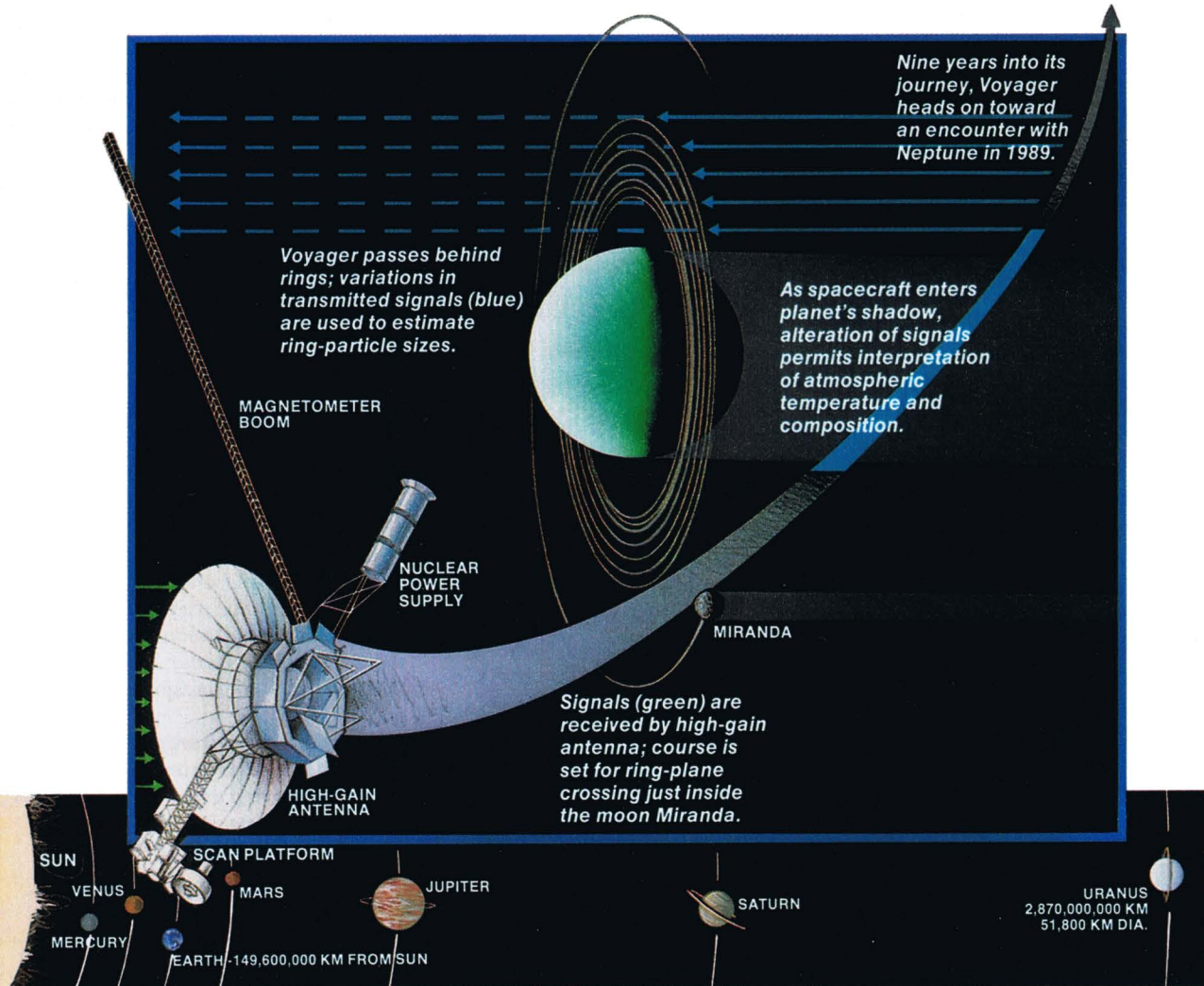
Ariel, the next moon out, shows a crust cracked by sinuous valleys. Glaciers appear to have flowed through those chasms.

Oberon, bland except for scattered craters, better fits the classic picture of an ice moon. Puzzlingly, some craters have been flooded by a material as black as the Uranian rings.

A great trench scars much of Titania's face, and many small craters make it look old. But Titania lacks the large impact craters typical of ancient surfaces elsewhere in the solar system.

Umbriel, at first appearing unmarked and relatively young, proves to be peppered with old craters 50 to 100 kilometers across. Yet it still looks blanketed by more recent debris.

January 26. Voyager scientists are confronted with new perplexities about the rings of Uranus. Although a thin tenth ring had already been discovered, specialists knew that details in the dark rings would be hard to see. Compared with Saturn's



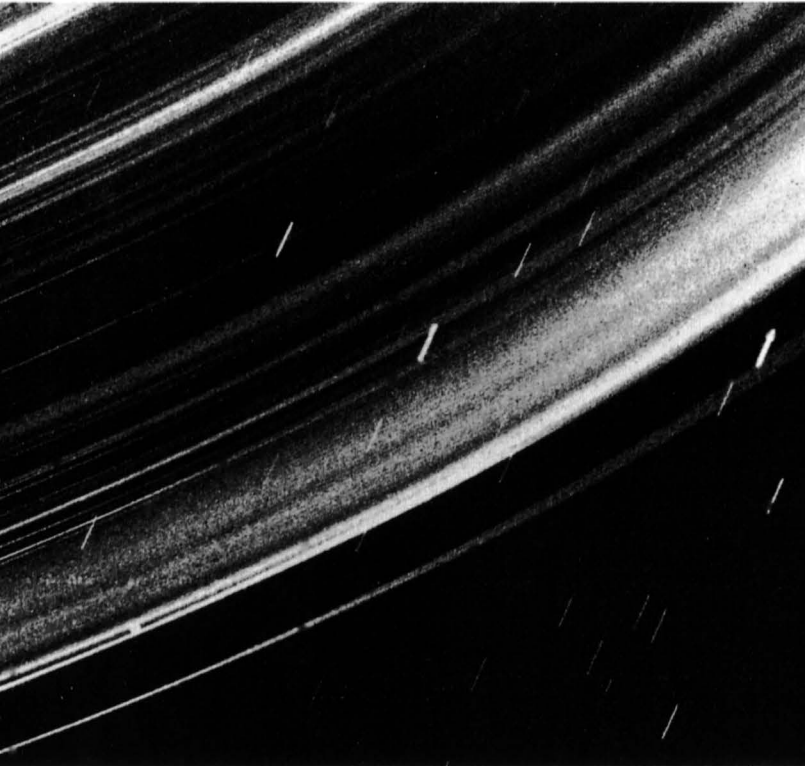
PLANETS AND ORBITS NOT TO SCALE; FIGURES ARE AVERAGE DISTANCES FROM THE SUN

showy bands, which can measure tens of thousands of kilometers across, Uranian rings are thin strands. The irregular Epsilon ring, widest and outermost, ranges between a mere 20 and 100 kilometers wide.

Scientists had hoped to confirm a theory that between 10 and 18 small shepherd moons gravitationally confine and clear gaps between all nine known Uranian rings. At least three such moons had been discovered at Saturn. But at Uranus only one ring is obviously shepherded.

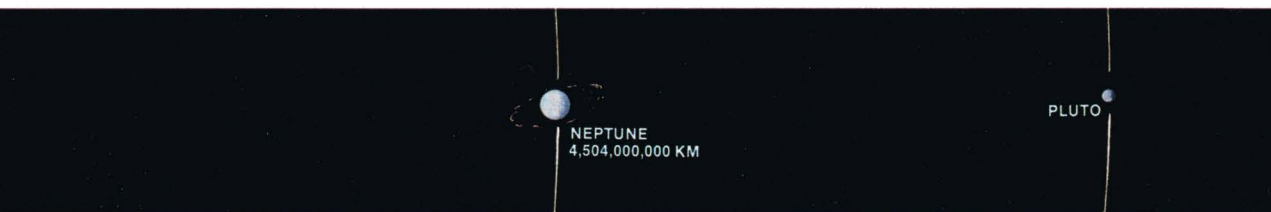
Would the scientists see strange formations of dust, as they unexpectedly had at Saturn? There the dust had been arrayed in kinks, braids, spokes, and other patterns. But at Uranus, Voyager has found no dust at all. Now the ring specialists are pinning their last hopes on an extremely long—96-second—exposure that Voyager will take looking back at the planet. With the sun in the background, tiny dust particles should scatter sunlight, much as strands of hair create an aura around the head of a person standing before the sun.

And indeed, a spectacle of about a hundred dust ringlets emerges. Someone jokes that a picture of Saturn's rings must have been put on the monitor by mistake. Even as they debate



*Two shepherds, moons not 50 kilometers across (above), confine by their gravity the outermost of the nine rings known before Voyager's arrival. But what confines the other rings—undetected shepherds still smaller?*

*For the most part the rings are made up of fairly large objects—boulder to house size—but when Voyager ducked behind the rings, it made a 96-second exposure (left) that revealed lanes of dust and other ring details (short streaks are star images). What keeps the whole carousel of rings and dust in such orderly and well-defined lanes remains to be discovered.*





Impact sunders Miranda, but the fragments remain in nearby orbits and reaccrete.



Gravity reforms Miranda into a lumpy sphere, but there is not enough heat to melt the pieces completely.

# Violent rebirth of a moon

*Titanic collisions—five or more—disrupted Miranda, shattering the moon's surface and scrambling its innards.*

*The above sequence depicts the most recent catastrophe, which produced the features observed by Voyager. Just short of 500 kilometers in diameter, this innermost and smallest of Uranus's five large moons is hit by a large piece of planetary debris. Miranda is able to reassemble itself, though its appearance is radically altered.*

what might create all this dust and organize it into ringlets, the ring specialists also must explain a broad new band that Voyager detected as it passed through the ring plane. About 2,500 kilometers wide, this new band orbits well inside Uranus's other rings and may be composed of marble-size chunks.

Particles of that size, which are dominant at Saturn, until now have been undetected at Uranus. In fact, measurements indicate that the Epsilon ring is made up almost entirely of black boulders, many the size of a house or larger. Since big boulders inevitably collide and grind down, where are the resulting little chunks? Could they all be swarming inward to join the newly discovered inner band?

**T**UESDAY, JANUARY 28. As Voyager scientists are preparing to sum up the mission for the press, the space shuttle *Challenger* explodes. Those clustered in JPL's press center share a horrible irony. On one monitor we watch replay after replay of seven lives evaporating over the Atlantic, while on an adjacent TV screen we see the latest triumphant pictures from Uranus.

As the nation mourns, Voyager's glory is eclipsed. But by mid-February Voyager scientists are preparing their first reports on what the spacecraft saw.

"We have more loose ends than with either the Jupiter or Saturn encounters," says the project's chief scientist, Ed Stone. "That's because we didn't know enough about Uranus going in to digest all the data as quickly."

For instance, Voyager revealed that the entire daylight face of