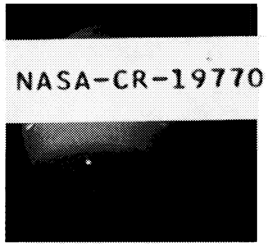
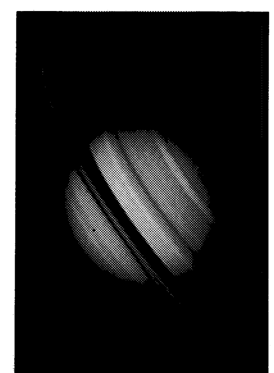


Voyager

The Grandest Tour

The Mission to the Outer Planets



Voyager

Foreword

On the cover:
Unforgettable images from the Voyager journey.

Center:
Earth and Moon (Voyager 1).

Clockwise from top left:
Neptune (Voyager 2), Uranus (Voyager 2), Saturn (Voyager 2), Jupiter (Voyager 1).

A The Sun lights a crescent of Uranus to a departing Voyager 2.

B False color increases the visibility of features in Saturn's North Temperate Belt.

C The Voyager spacecraft were the most complex unmanned machines ever built at JPL.

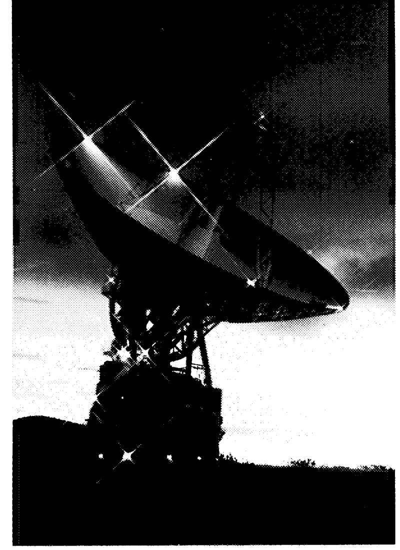
D The south polar region of Jupiter's moon Io, seen by Voyager 1 as it passed beneath.

Written accounts have described them as loyal, fearless, intelligent and curious. They have been called intrepid. Indefatigable. Troupers, they are both still operating smoothly years beyond their planned lifetimes. One has even been dubbed "the little robot that could."

The machines that have inspired such imaginative and sometimes anthropomorphic descriptions are the United States' Voyager 1 and Voyager 2, a pair of gangly, instrument-laden spacecraft assembled from more than 65,000 parts made in industrial and research laboratories across the country. The Voyagers' awkward looks belie the balletic grace with which they have conducted their explorations.

Over the course of 12 years, these spacecraft drew back the curtain on nearly half the solar system. They brought into sharp focus the faces of the four giant outer planets — Jupiter, Saturn, Uranus and Neptune — and their families of disparate moons. The Voyagers showed us unimagined worlds: frozen beauty in the rings of Saturn, and molten violence in the explosive sulfur volcanoes on Jupiter's moon Io. They brought us close-ups of the florid and intricate storms of Jupiter itself. Voyager 2 went on to reveal the peculiarities of cockeyed Uranus and its equally skewed rings and moons. Then finally, Neptune, nearly invisible from Earth, was unveiled in all its big, blue splendor, circled by shadowy rings and a bright pastel moon called Triton.

Voyager THE MISSION



The Voyager spacecraft, originally meant to fly by just two planets and operate for five years, accomplished much more. In all, they explored four planets, tens of moons and the rings and magnetic environments of those planetary systems. The mission became one of those technological enterprises that actually delivered more than it promised. Together, the Voyagers and the men and women who built the spacecraft and choreographed their flight accomplished one of history's most ambitious and rewarding expeditions of discovery.

The Voyager mission, managed for the National Aeronautics and Space Administration (NASA) by the California Institute of Technology's Jet Propulsion Laboratory (JPL) in Pasadena, California, was designed to take advantage of a rare geometric arrangement of the outer planets — one that occurs only once every 176 years. This layout of Jupiter, Saturn, Uranus and Neptune allows a spacecraft to swing from one planet to the next without the need for large onboard propulsion systems; the flyby of each planet both accelerates the spacecraft and bends its flight path. Aimed properly, the spacecraft can be sent on to the next planet. Without this "gravity assist" technique, the flight time to Neptune is 30 years; with it, only 12.

While a four-planet mission, promoted by planetary scientists as the "Grand Tour," was known to be possible, it was deemed too expensive to build a spacecraft that could travel the distance, carry the instruments needed and last long enough to complete such an extended voyage. Thus, the project was funded to conduct intensive flyby studies of only Jupiter and Saturn. More than 10,000 trajectories were studied before the two were chosen that would allow close flybys of Jupiter and its large moon Io, as well as of Saturn and its rings and large moon Titan. The chosen flight path for Voyager 2 also preserved the option to continue on to Uranus and Neptune.

A The Mars antenna in California's Mojave Desert is shown in its 210-foot-diameter configuration.

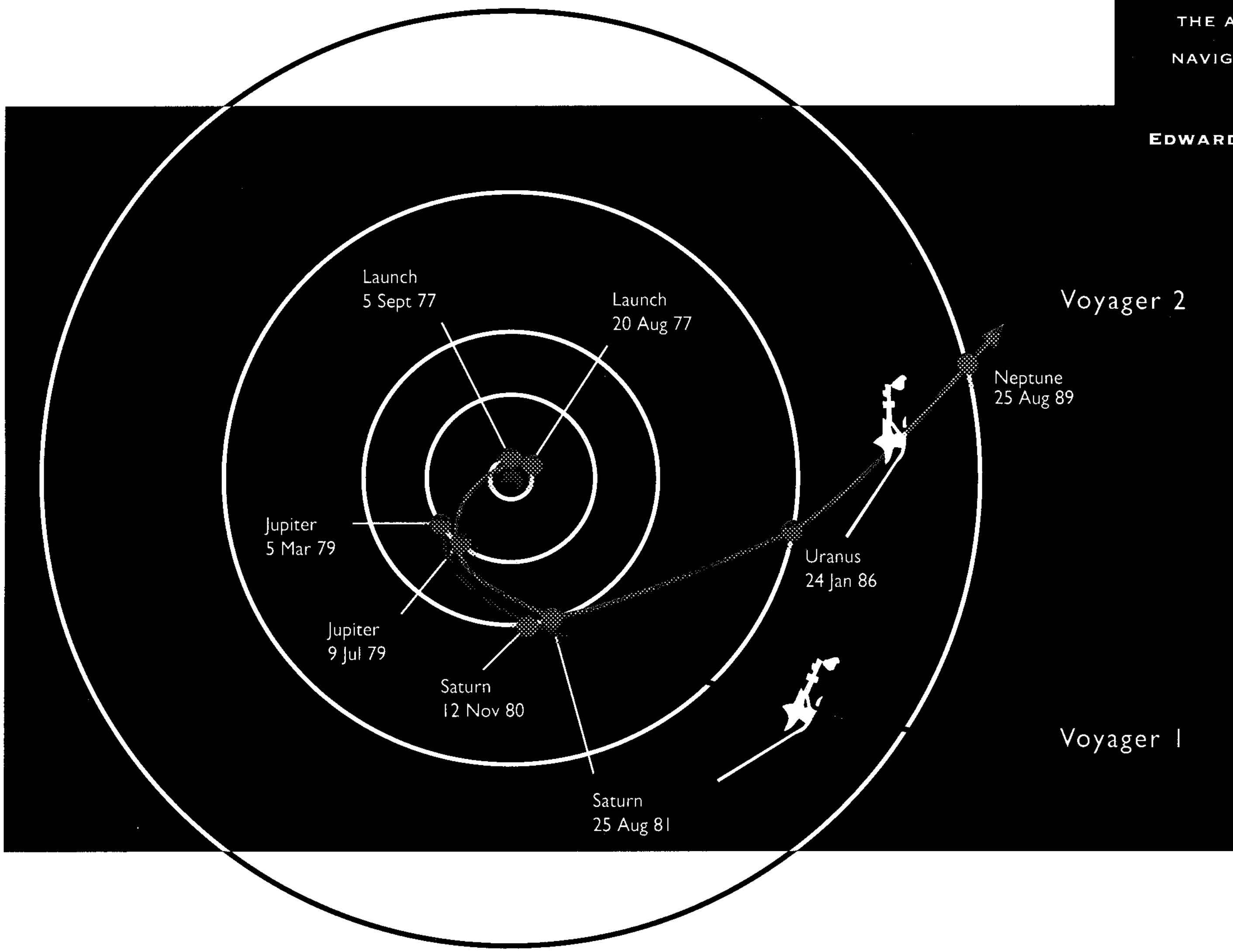
B A heliocentric view of the Voyager trajectories. The spacecraft are now on an eternal journey toward interstellar space.

Sights and sounds of Earth appear on records aboard the Voyagers — as a message from our planet

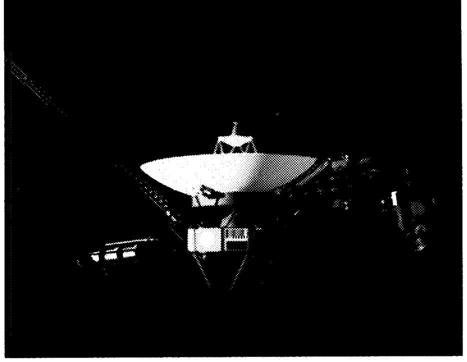
THE WIND AND THE WAVES ARE ALWAYS ON THE SIDE OF THE ABLEST NAVIGATORS.

EDWARD GIBBON

B



Voyager



Aboard a Titan/Centaur expendable launch vehicle, Voyager 2 was launched first, on August 20, 1977. Voyager 1 — also on a Titan/Centaur — was launched on a faster, shorter trajectory on September 5, 1977. Both launches were from the NASA Kennedy Space Center at Cape Canaveral in Florida.

All the unmanned spacecraft that came before them, whether they flew or failed, contributed to the mechanical stamina and electronic adaptability built into the Voyagers. The key to the Voyagers' success lay in this heritage, and in the acknowledgment that things could go wrong. By installing backups, or providing what spacecraft engineers call "redundancy," to take over in the event of the failure of critical components such as radio receivers and computers, Voyager engineers launched the spacecraft with the foresight of a driver who embarks on a cross-country trip having packed extra hoses, filters and a spare tire in the trunk.

In mid-December 1977, just after entering the asteroid belt, Voyager 1 overtook Voyager 2

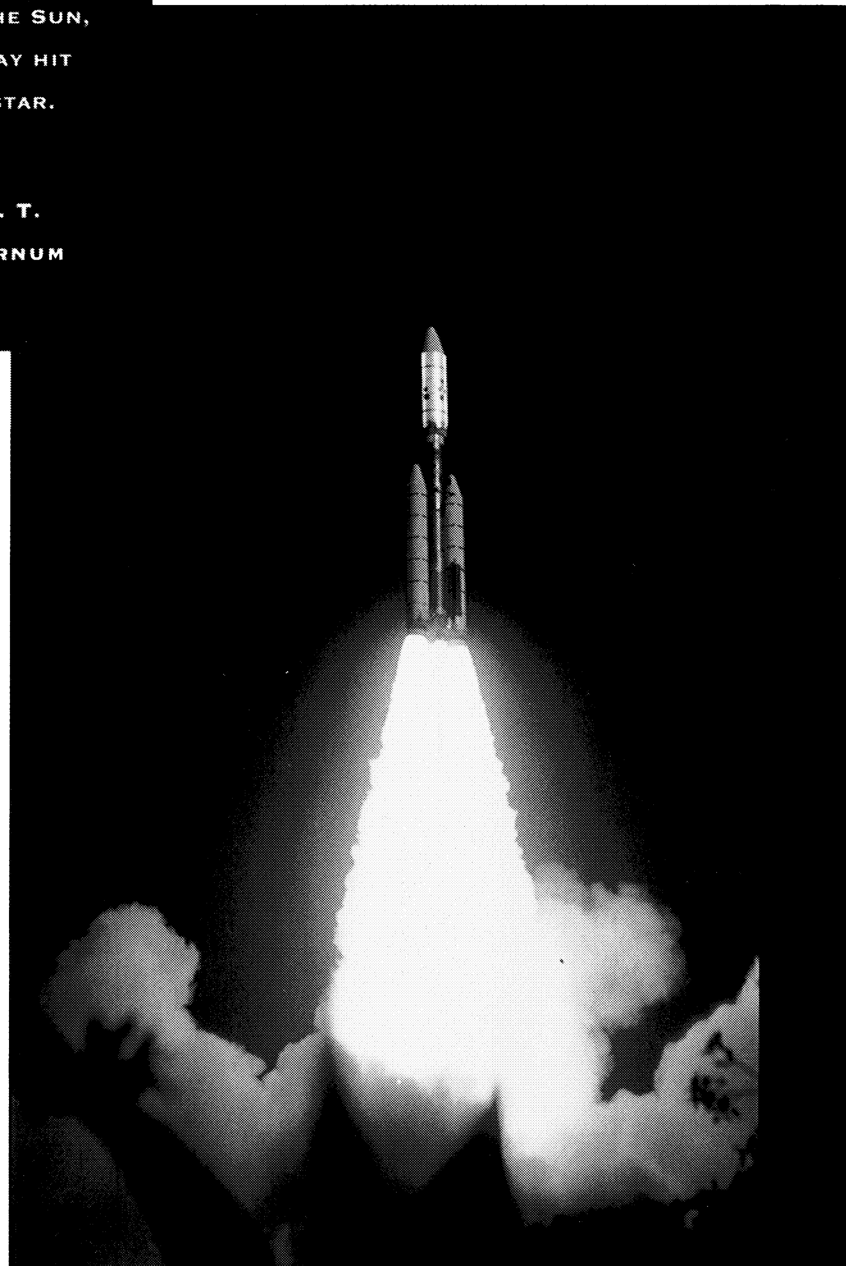
(A) Voyagers 1 and 2 are identical Mariner-class spacecraft, each weighing 1,820 pounds and carrying 11 science instruments.

(B) In summer 1977, a Voyager leaves Earth atop its Titan/Centaur expendable launch vehicle.

(C) Voyager 1 took the first single-frame photograph of Earth and the Moon.

If I shoot
at the Sun,
I may hit
a star.

P. T.
Barnum



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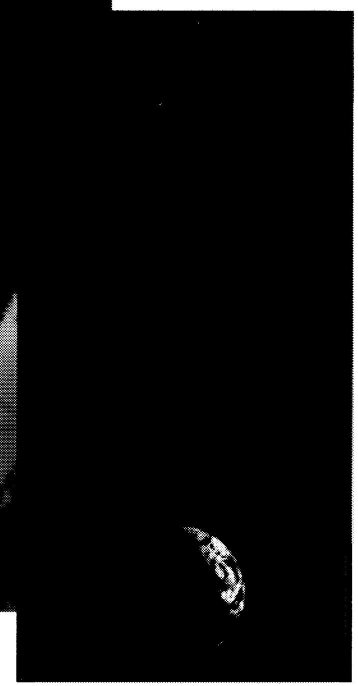

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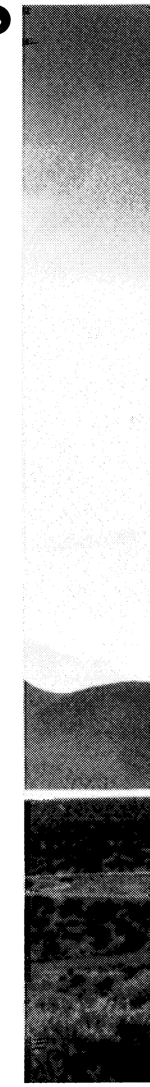


This prudence paid off early in the mission when Voyager 2's prime receiver failed. For the rest of its flight, telecommunications with Voyager 2, conducted through the Deep Space Network (DSN) operated for NASA by JPL, depended on a flawed but functional backup receiver.

Demands placed on the Voyager spacecraft grew with the distance they traveled from Earth. Commands from the DSN transmitters, traveling at the speed of light, took longer and longer to reach the spacecraft; correcting any mistakes or attempting to remedy a problem on the spacecraft entailed uncomfortably long delays before the spacecraft received and executed the necessary commands and then radioed back to Earth that the problem had been solved. At Jupiter, the Voyagers were less than an hour's light-time away, but by the time Voyager 2 reached Neptune, it took more than four hours to make the radio connection from Earth. The spacecraft were programmed to orient themselves in a "safe" state — instruments pointed away from the Sun, radio dish pointed toward Earth ready to receive commands — whenever any spacecraft maneuver or normal operations did not go as planned. The ability to detect flaws in the execution of their programs and to place themselves in a safe state whenever anything went awry was of critical importance in keeping the Voyagers healthy over their long journeys.

A THE MARS ANTENNA WAS ENLARGED FROM 210 TO 230 FEET IN DIAMETER FOR VOYAGER 2'S 1989 ENCOUNTER WITH NEPTUNE.

B REMOTE DESERT LOCATION AND SURROUNDING HILLS PROTECT THE SENSITIVE DSN RECEIVERS FROM EARTH-BASED RADIO "NOISE" THAT WOULD OVERWHELM SPACECRAFT SIGNALS.

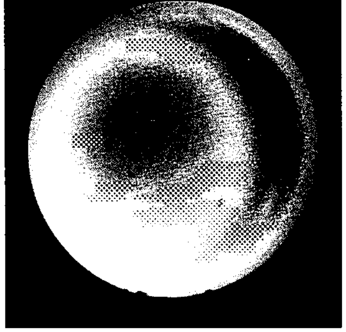
C THE ANTENNA'S SECONDARY MIRROR, SUPPORTED BY THE TOWER, REFLECTS RADIO SIGNALS DOWN TO THE RECEIVER IN THE CENTRAL CORE.

A SINGLE VOYAGER IMAGE CONTAINS UP TO 5.12 MILLION BITS OF DATA

Time is
the longest
distance
between two
places.

Tennessee
Williams

C

A 

Jupiter, Saturn, Uranus and Neptune are giant planets with deep atmospheres made up primarily of hydrogen and helium. They and their moons and rings formed and have evolved in a much colder, darker region of space than the inner planets of the solar system. None of these outer planets has a solid surface. At their centers are spheres of molten ice and rock.

With a diameter of 88,846 miles, Jupiter is the largest planet in the solar system. Sulfur compounds and ammonia give its atmosphere its yellow and orange hues and white clouds. Saturn, second largest with a diameter of 74,900 miles, lacks the chemicals in the upper atmosphere that give Jupiter its colors. Saturn has less inherent color, reflecting mainly the pale yellow of the Sun. Uranus is 31,764 miles in diameter, making it the third largest. Neptune is close behind with a diameter of 30,776 miles. Methane in their atmospheres gives these last two planets their blue tones. Besides studying them for their own sake, scientists consider other planets to be laboratories where different facets of the early history of Earth and the solar system as a whole can be explored and theories can be tested.

EACH YEAR, VOYAGER 1 TRAVELS THREE-AND-ONE-HALF TIMES THE DISTANCE FROM EARTH TO THE SUN

As different as the outer planets and their moons are from Earth and other bodies closer to the Sun, they all share certain characteristics and physical processes. The field of comparative planetology investigates the common threads linking the pasts and futures of the planets, their systems of moons and rings and their magnetic environments. Processes observed on one body can be extrapolated and applied to another. For example, studying and comparing the meteorology of the outer planets can help scientists understand the basic forces that control climate and weather on Earth. Studies of the large moons of the outer solar system help divulge the geophysical processes common to solid bodies. Studies of small moons and planetary rings reveal information about how the solar system formed and how it has evolved.

A IMAGES OF URANUS WERE COMBINED AND PROCESSED TO ENHANCE VARIATIONS IN THE PLANET'S ATMOSPHERE.

B CLOUDS IN NEPTUNE'S ATMOSPHERE: THE GREAT DARK SPOT AND A BRIGHT WHITE CLOUD ARE JUST LEFT OF CENTER.

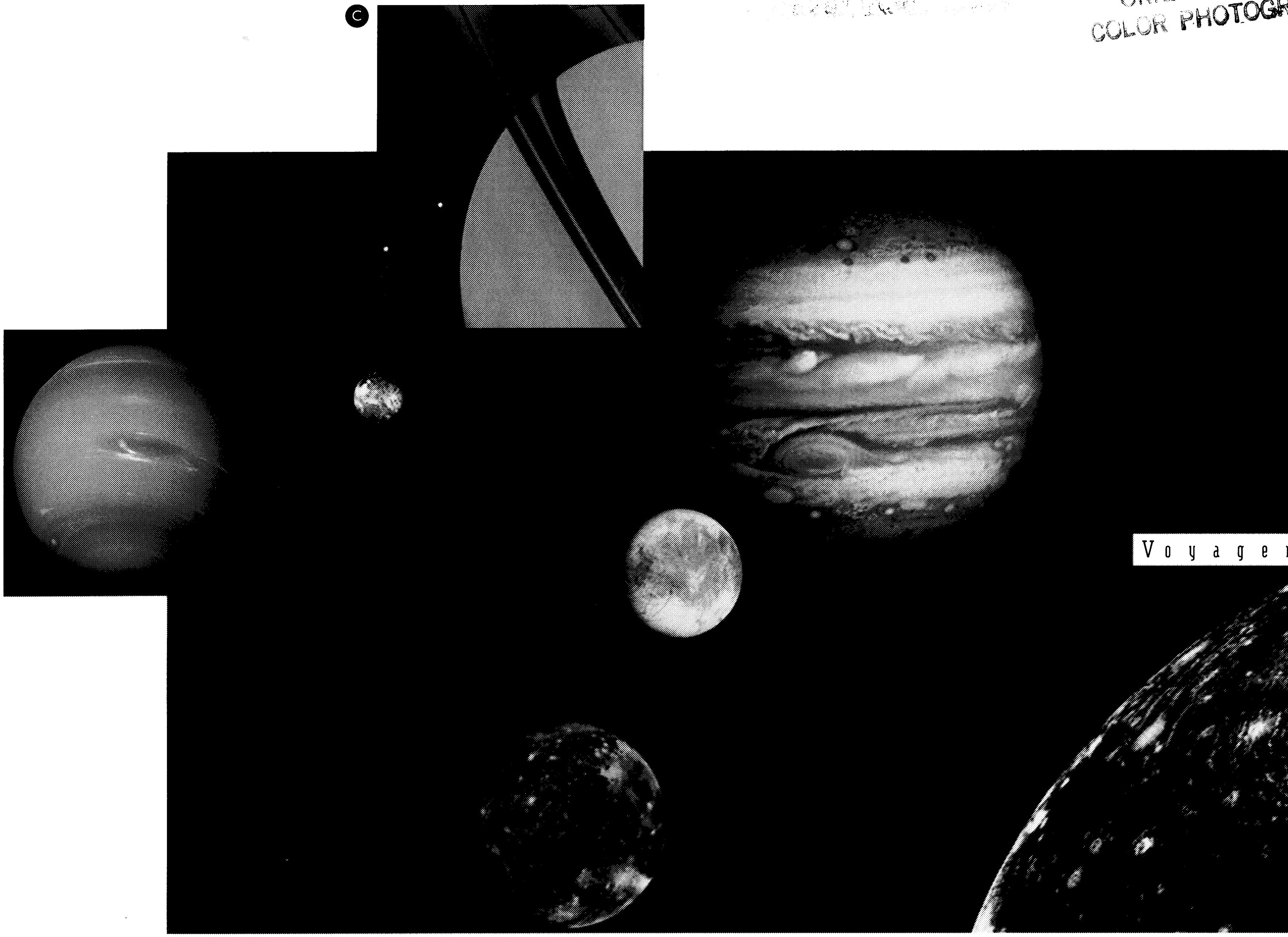
C SATURN, WITH MOONS TETHYS (ABOVE) AND DIONE, AS CAPTURED BY VOYAGER 1.

D A MONTAGE OF JUPITER AND THE FOUR GALILEAN SATELLITES. FROM LEFT ARE IO, GANYMEDE, EUROPA AND CALLISTO.

C

D

B



As the closest of the four giant planets, Jupiter was better known than the others before the Voyagers arrived. Studied through telescopes since Galileo, the broad, visible characteristics of the Jovian system — the Great Red Spot and the latitudinal bands — were apparent, as were the four Galilean moons, so-called because of their discovery by the 17th-century Italian astronomer. Eight other moons also could be counted. Beyond the visible features of the Jovian system was the intense radio noise emitted from the planet. The noise, which is due to electrons spiraling in Jupiter's magnetic field, is loud enough to make Jupiter the second noisiest radio emitter in the solar system, after the Sun.

NASA's Pioneer 10 and 11 spacecraft preceded the Voyagers to Jupiter in the early 1970s and sent back important information about the powerful Jovian magnetic environment, including measurements of the searing radiation belts around the planet. The Pioneer experience at Jupiter led Voyager engineers to take extra measures to harden the spacecraft's electronic components against radiation.

Voyager 1 took 18 months to reach Jupiter, 400 million miles away. The spacecraft made its closest approach on March 5, 1979, while Voyager 2 followed on July 9 the same year. A torrent of new discoveries began as the spacecraft neared the giant planet.

The ultraviolet spectrometer observed auroral activity so intense it was detectable on the day side of Jupiter. As on Earth, the auroras are caused by charged particles plunging into the atmosphere.

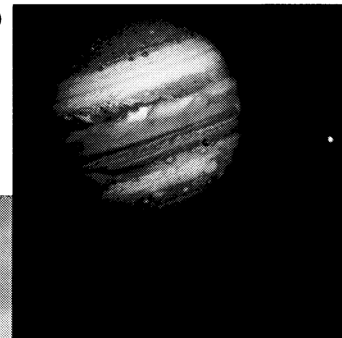
A

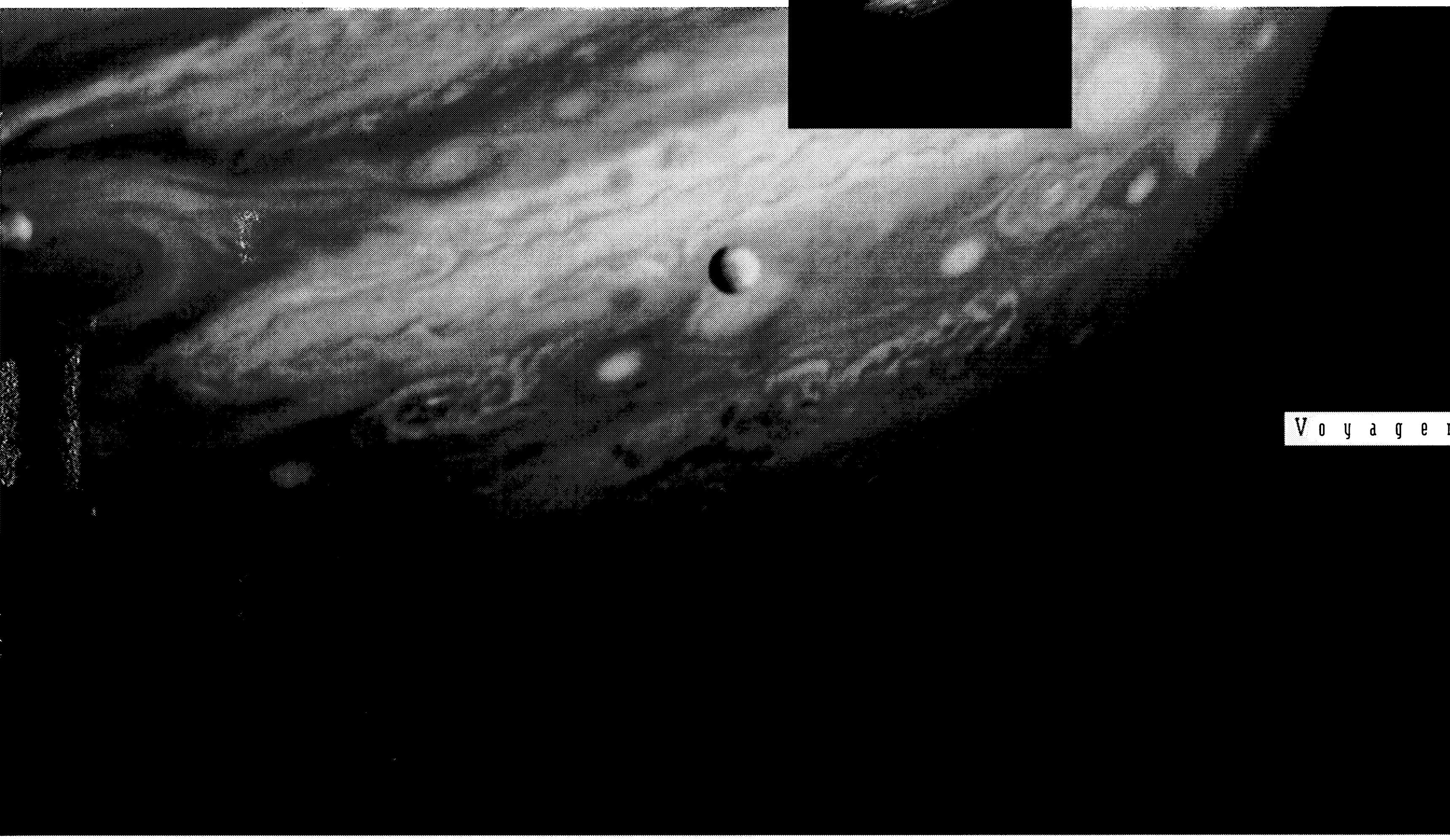
A IO (LEFT) AND EUROPA, PASSING BEFORE THE GREAT RED SPOT, LARGEST OF JUPITER'S MANY STORMS.

B RED-ORANGE IO AND WHITE EUROPA ORBITING ABOVE JUPITER'S MULTIHUED CLOUDS.

THE VOYAGERS TOOK NEARLY 33,000 PHOTOGRAPHS OF JUPITER AND ITS SATELLITES

B





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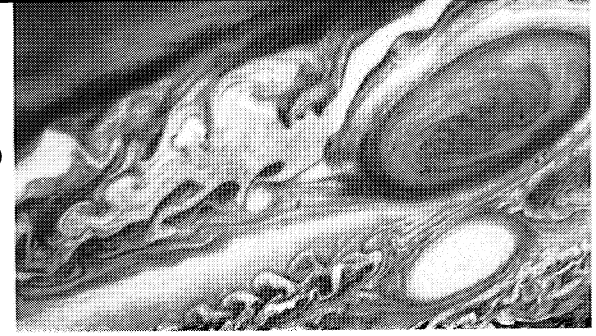


The complicated, swirling turbulence of the atmosphere and its beauty, reminiscent of works by Vincent van Gogh, awed scientists and non-scientists alike. The yellow, red and orange belts around Jupiter were shown to contain roiling, fluid-like storms. Huge cyclones moved through the upper atmosphere. A white jet stream of ammonia crystals clipped along at 350 miles per hour. The Great Red Spot, a hurricane-like storm three times the size of Earth, was seen surrounded by swirling currents that rotated around the spot and were sometimes consumed by it. The color of the spot, still unexplained more than a decade after the Voyager flybys, may be due to traces of sulfur or phosphorus compounds.

Nothing in Jupiter's realm was as exotic or more unexpected than the discovery of active volcanoes on Io; it was the first time these had been spotted on any object in the solar system besides Earth. In March, Voyager 1's cameras saw nine volcanoes spraying sulfurous ejecta above the surface of the innermost Galilean moon. When Voyager 2 arrived four months later, eight of those volcanoes were still erupting. Io's volcanism explained its orange, red and black pepperoni-pizza appearance. The spots were not some kind of strange impact crater, but probably lakes of molten sulfur.

Io occupies an orbit that makes it the perpetual object of a gravitational tug-of-war between Jupiter and the moon Europa. In the same way that the Moon raises tides in Earth's oceans, Jupiter's gravity raises a bulge in Io's waterless surface. The tidal flexing of Io's crust heats the moon's interior and creates volcanic eruptions of sulfur and sulfur dioxide.

The next moon out is Europa. Its thin, icy crust is only weakly heated by tidal flexing, yet a tidally heated ocean may lie beneath the surface. The Voyagers found Europa's face to be remarkably smooth and uncratered, yet striated with lines that are probably fractures in the ice surface.

A JUPITER'S ATMOSPHERE OF VIOLENT STORMS AND SWIRLING EDDIES, INCLUDING THE GREAT RED SPOT AT UPPER RIGHT.

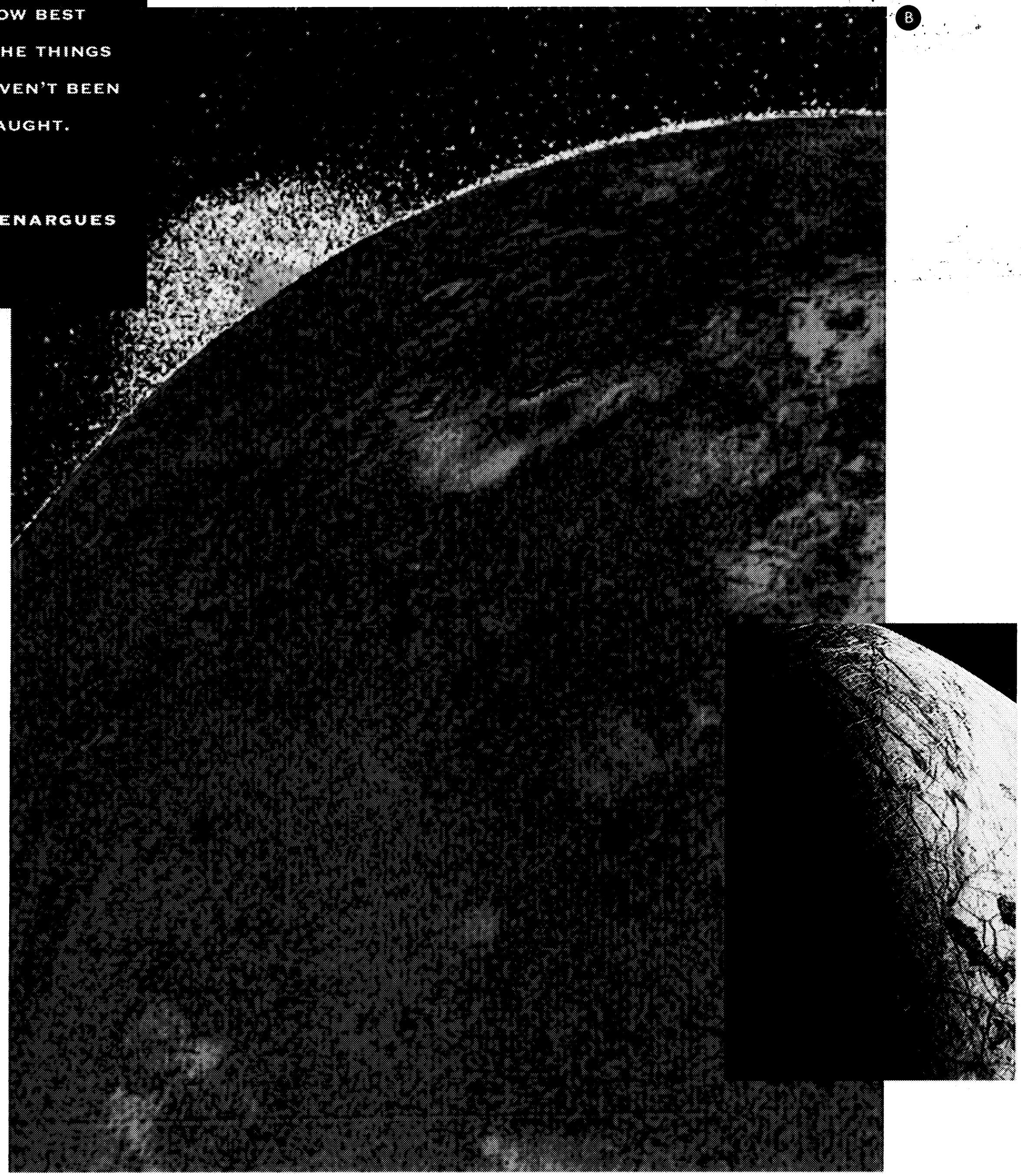
B LOKI, ONE OF NINE VOLCANOES SEEN ERUPTING ON IO AS VOYAGER 1 FLEW PAST THE SATELLITE.

C THE ICY, CRUSTED SURFACE OF EUROPA IS LACED WITH LINES AND MAY HAVE MELTED LONG AGO.

225-MILE-PER-HOUR WINDS STREAM AROUND THE OUTER RIM OF THE 16,000-MILE-LONG GREAT RED SPOT

THE THINGS WE KNOW BEST ARE THE THINGS WE HAVEN'T BEEN TAUGHT.

VAUVENARGUES



B

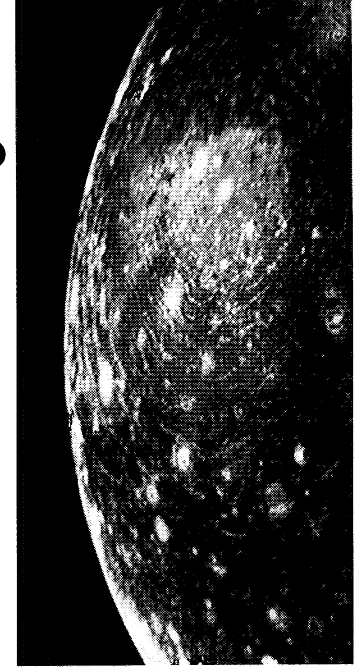
C

Ganymede and Callisto, both about the size of Mercury, are each half rock and half ice. When all the major moons in the solar system were finally measured by the Voyagers, Ganymede turned out to be the largest, with a diameter of 3,280 miles. Global tectonic processes appear to have been at work on this large body, creating crisscrossing ridges. These rifts, created by geophysical upheaval, surround other older, cratered terrain.

Callisto has escaped the geophysical transformation the other Galilean moons have undergone, and instead retains all of its original surface, still scarred by the rains of debris that littered the nascent solar system. This heavily cratered relic from the earliest days of the planets possesses one of the oldest surfaces in the solar system.

Much to the surprise of Voyager scientists, a ring was found around Jupiter. Although suggested by Pioneer 11 data, the finding was unexpected; the theory explaining the long-term stability of planetary rings did not predict the existence of a thin, dusty, Jovian ring. Two of the three small moons the Voyagers found orbiting between Io and Jupiter appear to shed the dust-size grains that form the tenuous ring. Ultimately, new theories about rings were developed as the spacecraft found unique ring systems at each of the four giant planets.

A



A CALLISTO, THE OUTERMOST GALILEAN SATELLITE, FEATURES A HUGE, MULTIRINGED IMPACT STRUCTURE THAT RESEMBLES IMPACT BASINS ON THE SURFACE OF THE MOON.

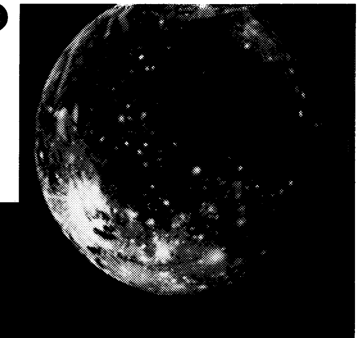
B THE JOVIAN RING SPARKLES AS VOYAGER 2 LOOKS AT THE DARK SIDE OF THE PLANET.

C GANYMEDE'S SURFACE SHOWS CONTRASTING, ANCIENT, DARK TERRAIN AND SOMEWHAT YOUNGER, LIGHTER TERRAIN.

D A MULTIPLE EXPOSURE OF JUPITER'S RING AND TRAILS OF DISTANT STARS APPEAR IN THIS RING-DISCOVERY PHOTOGRAPH BY VOYAGER 1.

THE OUTER EDGE OF JUPITER'S RING LIES 80,000 MILES FROM THE PLANET'S CENTER

C



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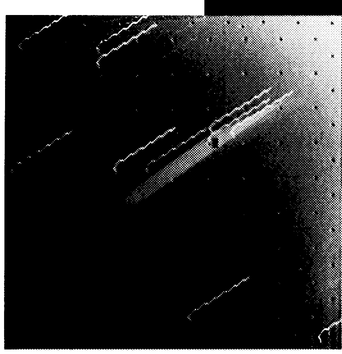
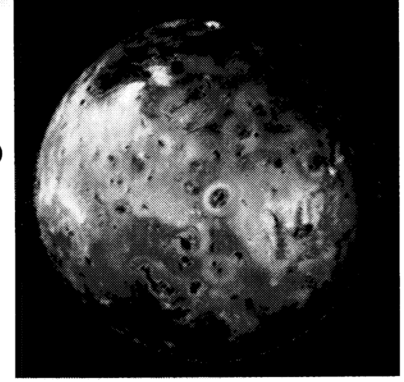


Jupiter



The largest entity in the Jovian system is the invisible force of the planet's magnetic field. Planetary magnetic fields are created by the motion of fluid interiors. Fifteen thousand miles deep within Jupiter's interior, hydrogen undergoes a dramatic change. At a pressure three million times that at Earth's surface, and at temperatures exceeding 19,000 degrees Fahrenheit, the hydrogen changes from molecular liquid to a state called liquid metallic hydrogen, an excellent electrical conductor. The liquid metallic hydrogen and the planet's rapid rotation (9 hours 55 minutes) generate electric currents that create Jupiter's magnetic field, which is more than 10 times stronger than that of Earth.

Jupiter's ring and moons are embedded in an intense radiation belt of electrons and ions trapped in the magnetic field. The Jovian magnetosphere, which comprises these particles and fields, balloons two or three million miles toward the Sun and tapers into a windsock-shaped tail extending at least 465 million miles behind Jupiter — as far as Saturn's orbit.

FINE DUST PARTICLES FROM TWO SATELLITES NEAR ITS OUTER EDGE COMPOSE JUPITER'S RING

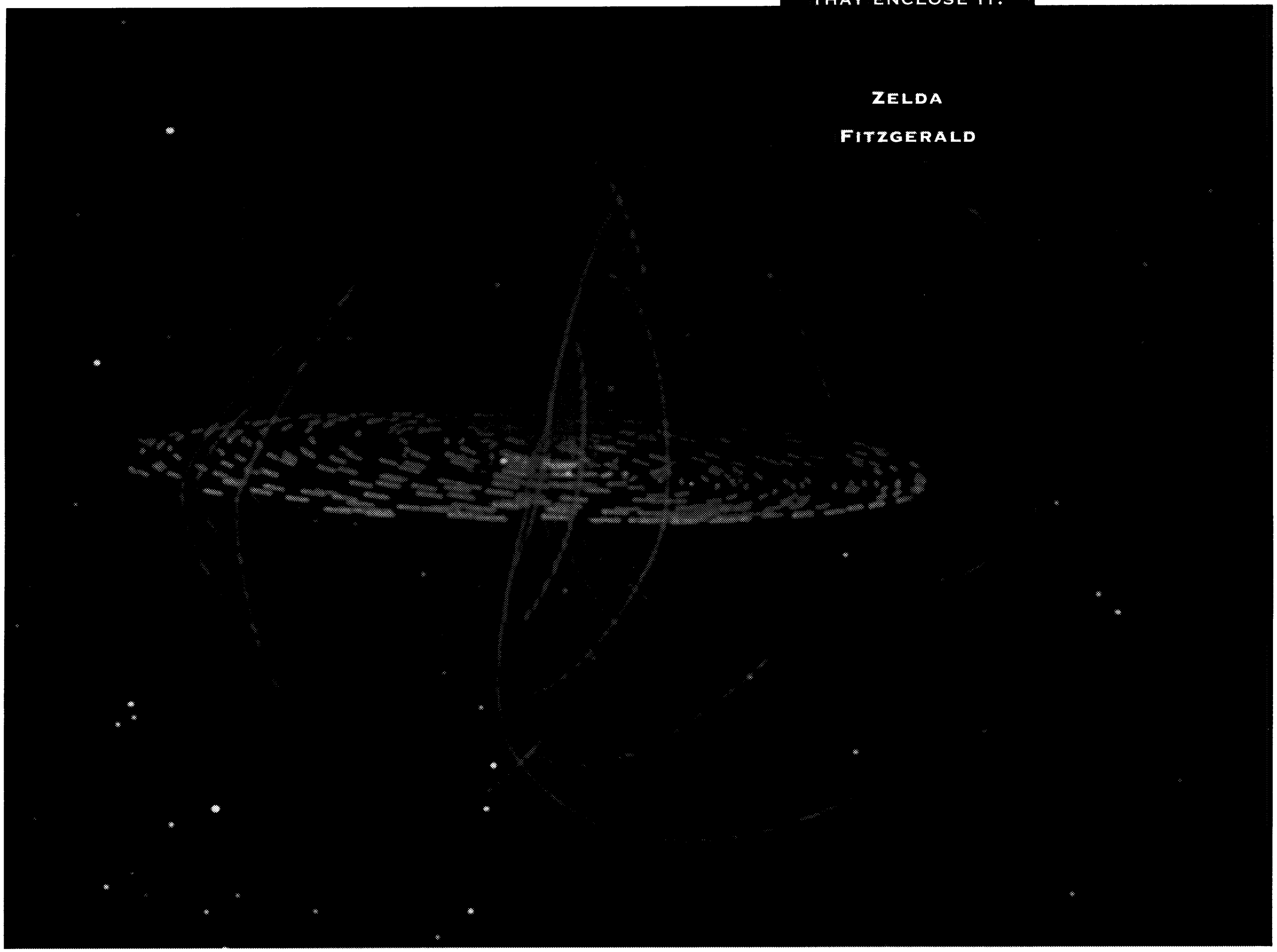
The relationship between the magnetic field and Io is unique. As the magnetosphere rotates with Jupiter, it sweeps past Io, stripping away about a ton of matter per second and forming a torus — a doughnut-shaped ring around Jupiter predominantly composed of electrified oxygen and sulfur glowing in the ultraviolet. As these heavy ions migrate outward, their pressure inflates the magnetosphere to more than twice its expected size. Some of the more energetic ions fall into the atmosphere along the magnetic field to create Jupiter's auroras.

As Io moves through Jupiter's magnetic field, it acts as an electrical generator, developing 400,000 volts across its diameter and generating an electrical current of three million amperes. The current flows along the magnetic field to Jupiter's ionosphere.

A IO'S VOLCANOES CONTINUALLY RESURFACE IT, SO THAT ANY IMPACT CRATERS HAVE DISAPPEARED.

B THE CENTRIFUGAL EFFECTS OF IO'S TORUS INFLATE JUPITER'S ALREADY IMMENSE MAGNETIC FIELD.

B



A VACUUM
CAN ONLY EXIST,
I IMAGINE,
BY THE THINGS
THAT ENCLOSE IT.

ZELDA
FITZGERALD

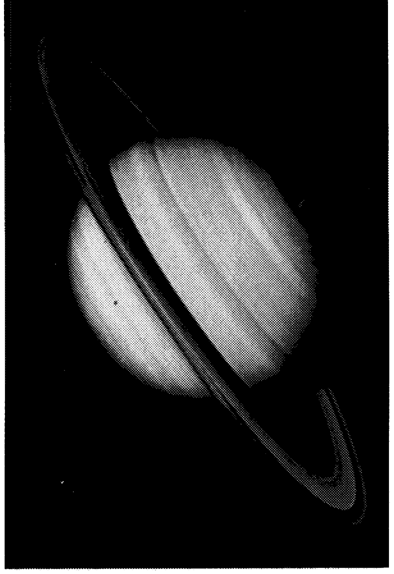
For 2,600 years, sky watchers have observed the slow progress of Saturn in its orbit around the Sun. Through his telescope, Galileo noted strange appendages on either side of the pale yellow planet that he took to be attendant bodies. Christiaan Huygens in 1655 concluded that the appendages were not attendants, but a ring encircling the planet. Later, astronomers would discover gaps separating a multiple-ring system. Scientists have long sought to determine what the rings are made of, how they got there and what keeps them in orbit around Saturn. Some of the questions began to be answered when Voyager 1 arrived at Saturn on November 12, 1980, and Voyager 2 arrived on August 25, 1981. But the Voyager discoveries would soon present many more new puzzles than solutions.

Saturn is composed of the same constituents as Jupiter, but in different mixtures. Saturn radiates 80 percent more energy than it absorbs from the Sun. The Voyagers found that the amount of helium in the atmosphere is less than half that at Jupiter, consistent with the suggestion that the precipitation of helium out of the mainly hydrogen atmosphere could be supplying the internal heat that Saturn radiates.

Even with its self-manufactured heat, Saturn's atmosphere, compared to Jupiter's, is much less turbulent and somewhat placid-looking. Given Saturn's relatively bland appearance, scientists were surprised at the high-velocity equatorial jet stream that blows some 1,100 miles per hour.

Computerized enhancement of some of the Voyager images made apparent Saturn's faint banding through the planet's hazy upper atmosphere, and several hurricane-like storm systems could be discerned. Saturn's greatest beauty and mystery, however, were not in its atmosphere, but in its rings; by the time the Voyagers reached and photographed the rings, they were acknowledged as the most exquisite sight in the solar system.

A



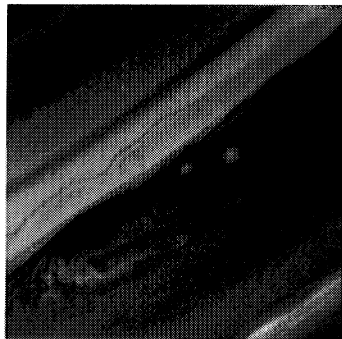
A THREE OF SATURN'S MOONS (TOP TO BOTTOM), TETHYS, DIONE AND RHEA, ARE VISIBLE. TETHYS' SHADOW APPEARS ON SATURN'S CLOUDS.

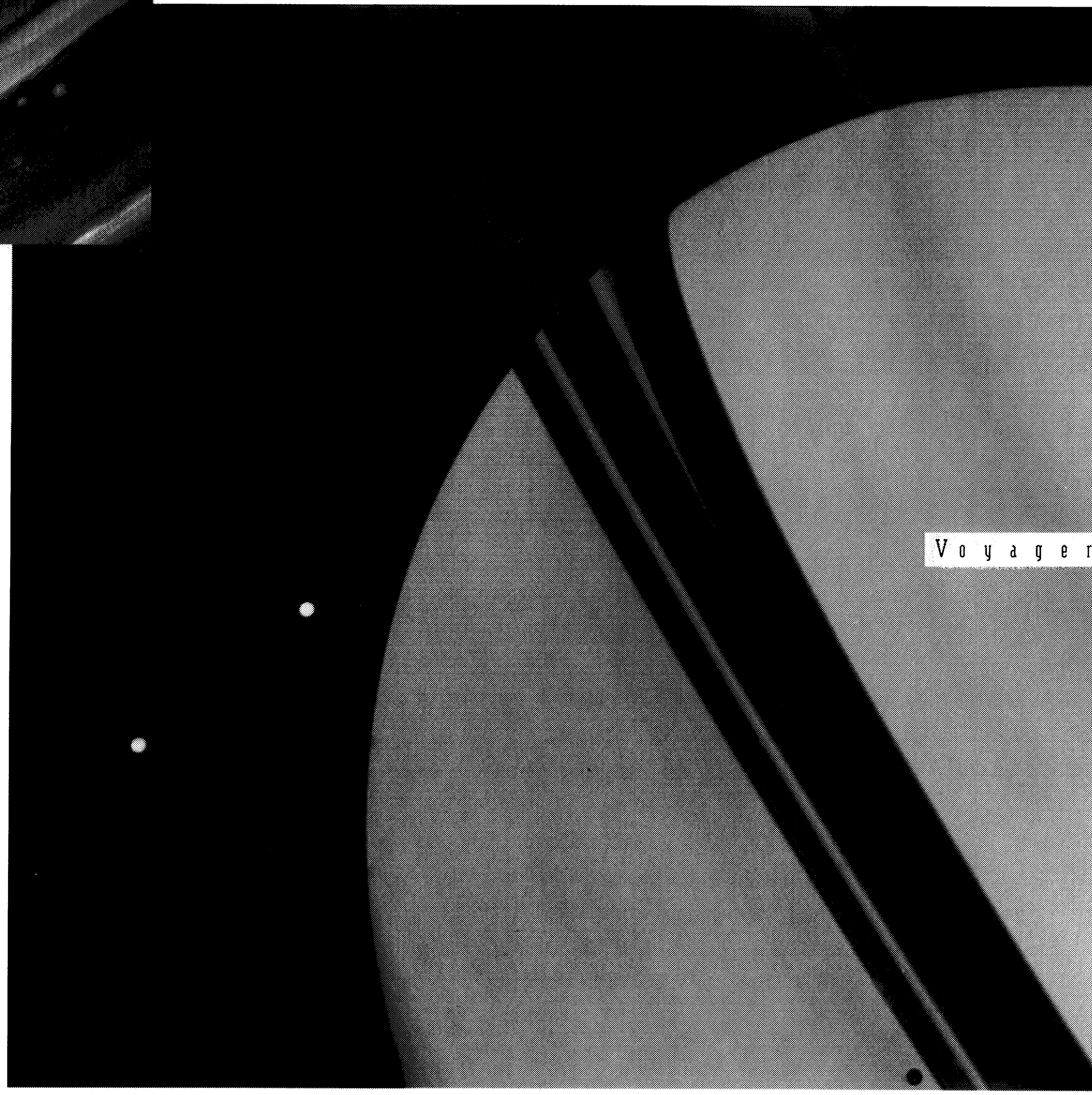
B A FALSE-COLOR IMAGE TAKEN THROUGH GREEN, VIOLET AND ULTRAVIOLET FILTERS SHOWS THREE LARGE STORMS IN SATURN'S NORTHERN HEMISPHERE.

C RINGS OF SATURN CAST A SHADOW ON THE PLANET'S SMOOTH SURFACE AS TWO ICY SATELLITES, TETHYS (ABOVE) AND DIONE, ORBIT.

SATURN'S DIVERSE FEATURES ARE MUTED BY A HAZY UPPER ATMOSPHERE

B





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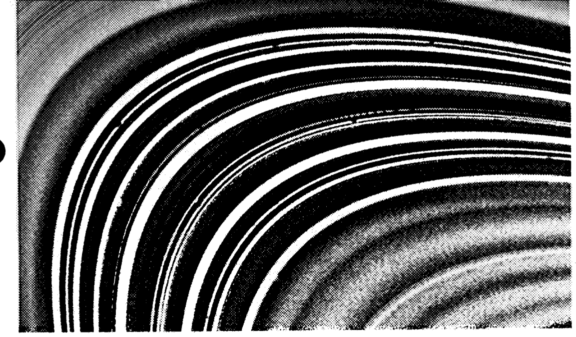


Rather than being broad, featureless sheets, the rings were found to have an intricate structure. Scientists were amazed by strange shadowy streaks crossing the broad B-ring and forming spoke-like patterns around the planet. These spokes, which appear to form, dissipate and reform in a matter of hours, possibly are small grains of dust electrostatically levitated above the larger particles. In time-lapse movies of Voyager images, the motion of the spokes revealed the rotation of the rings around Saturn. "We never thought we would be able to see the rings spinning like this," said one scientist. "We thought we would see the planet turning with the rings as a still life. It now appears to be more nearly the reverse." The material in the rings ranges from dust to boulder- and house-sized particles;

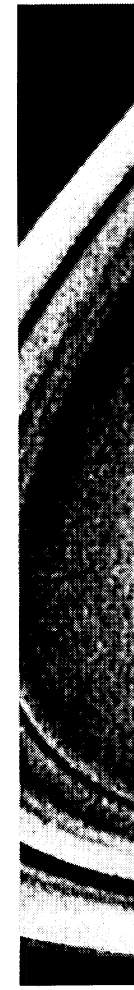
SATURN'S COUNTLESS, ICY, RING PARTICLES RANGE IN SIZE FROM DUST-SIZED GRAINS TO BOULDERS

the rings themselves are not much thicker than the largest particles and are thought to be the remnants of large moons that were shattered by impacts of comets and meteoroids. The irregular shapes of the smallest of Saturn's 18 known moons suggest that they too are fragments of larger bodies.

The Voyagers found several narrow gaps, some occupied by slender rings unseen from Earth. Kinks and wavy edges were discovered in some of the rings and were associated with "shepherding moons," small satellites orbiting within the ring plane. The elaborate and disordered structure of some of the rings is due largely to the gravitational effects of these moons, as demonstrated by the relationship between the F-ring and two small moons, Pandora and Prometheus, that orbit near one another but on opposite sides of the ring. These were the first of the many shepherding moons found orbiting the outer planets.

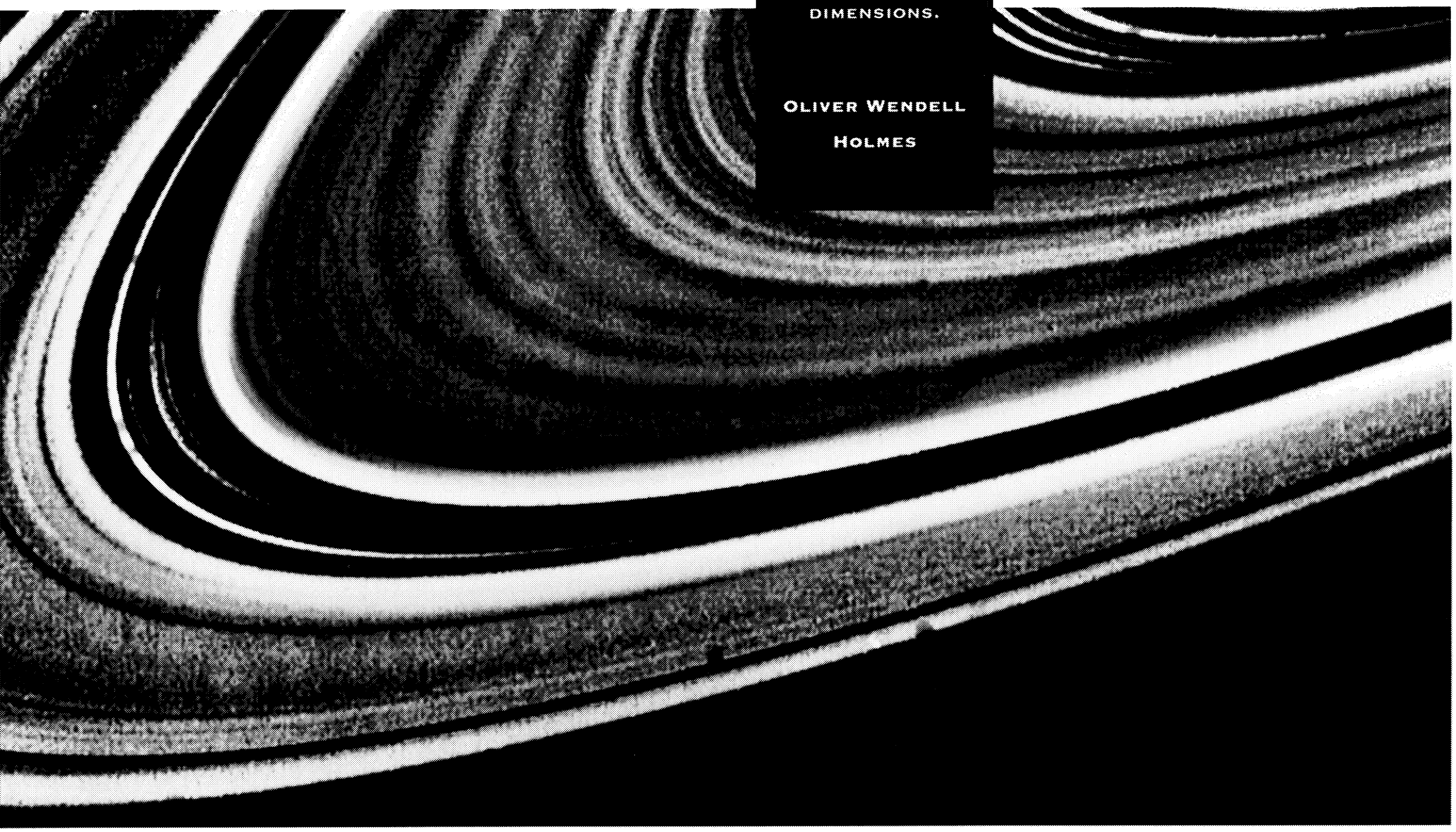
A THIS FALSE-COLOR PHOTOGRAPH OF SATURN'S B- AND C-RINGS REVEALS FINE DETAILS AND SUBTLE COLOR DIFFERENCES.

B THE INTRICATE COLOR VARIATIONS IN SATURN'S THREE MAIN RINGS ARE COMPUTER ENHANCED IN THIS VOYAGER 2 IMAGE.



A man's mind stretched by a new idea can never go back to its original dimensions.

Oliver Wendell Holmes



B

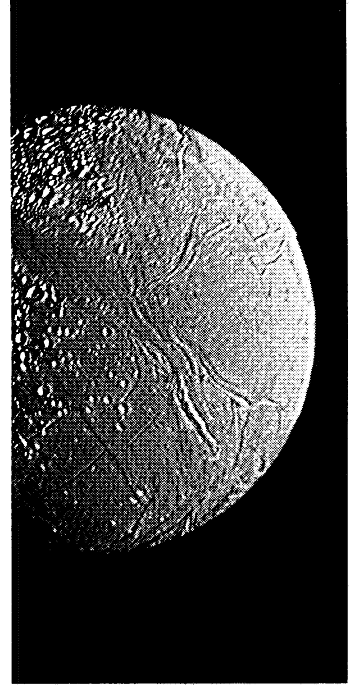
Moons embedded in the rings were found to sweep pathways clear of particles, creating the gaps between rings. In addition, the Voyagers found spiral waves in the rings, generated by the gravitational wake of moons orbiting outside the rings.

Titan, the largest moon of Saturn, has a diameter of 3,200 miles. It is covered with an orange photochemical haze too thick to see through, but Voyager scientists hoped for some openings that would allow a look at the surface. Although there were no such openings, instruments on the spacecraft provided intriguing glimpses of Titan that had scientists making early plans to send a probe to explore the terrain of the planet-size moon in the future. Because of uncertainty about whether Titan's surface is composed of oceans, lakes, dry land or some combination thereof, the probe to be parachuted into Titan's atmosphere early in the next century is being designed to land or float safely on anything ranging from liquid seas to solid ground.

Titan has been described as "Earth in a deep freeze." The chemistry in Titan's atmosphere may strongly resemble that on Earth before life evolved. Titan's surface temperature and pressure are –292 degrees Fahrenheit and 1.5 atmospheres, respectively. Photochemistry converts methane in the Titan atmosphere to other organic molecules, such as ethane, that are thought to accumulate in lakes or oceans. Other, more complex hydrocarbons form the haze particles that eventually fall to the surface, coating it with a thick layer of organic matter. Scientists believe this might be the kind of environment where, if it were warmer, primitive life might evolve.

The satellite with a history of the most surface activity is Enceladus. The many valleys and faults of this moon attest to its tectonic vigor. Likewise, Tethys has undergone internal stresses, as indicated by a valley extending more than half the moon's circumference. Another moon, Mimas, showed a crater so huge that the impact that caused it nearly broke the satellite apart.

A



A ENCELADUS' SURFACE MAY BE AN EXAMPLE OF CRYOVOLCANISM, FEATURING "LAVAS" OF WATER ICE AND OTHER SLUSHES.

B HAZES, SHOWN IN FALSE-COLOR BLUE AND ORANGE LAYERS, ARE FORMED BY ORGANIC PHOTOCHEMISTRY OCCURRING IN TITAN'S ATMOSPHERE.

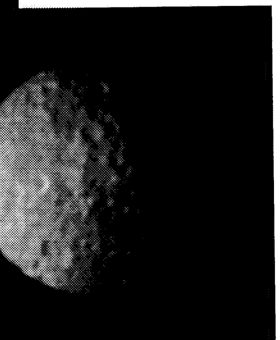
C MIMAS, ONE OF SATURN'S ICY SATELLITES, SHOWS A HUGE IMPACT CRATER ABOUT 81 MILES IN DIAMETER.

D A DARK RING AT ABOUT 70 DEGREES NORTH LATITUDE IN THIS VOYAGER 2 VIEW OF TITAN MAY BE AN EFFECT OF THE SPRING SEASON IN PROGRESS.

ETHANE IS CREATED IN TITAN'S ATMOSPHERE AND RAINS DOWN ONTO THE MOON'S SURFACE

B

C



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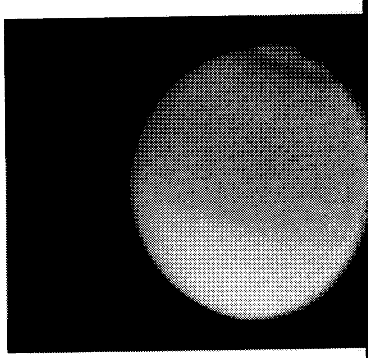

Saturn's magnetic field is only 5 percent that of Jupiter. Of all the magnetic fields studied by the Voyagers, Saturn's was the most orderly; the axis of the field is almost perfectly aligned with the rotational axis of the planet.

Titan is often embedded in Saturn's magnetosphere and sheds photochemically produced hydrogen to form a torus, somewhat similar to that produced by material swept off Io in Jupiter's magnetosphere. Ions from the surfaces of Saturn's icy moons form a sheet of ionized oxygen in the planet's equatorial plane.

Bursts of radio emission from Saturn were heard at a frequency of 10 hours 39 minutes, giving the length of a Saturnian day.

When Voyager 1 left Saturn, it left the planets forever, heading on a trajectory that took it northward, above the ecliptic plane in which the planets orbit the Sun. As it departed, Voyager 1 sent back stunning views of the dark side of Saturn, taken from a vantage point only a robot could reach. When Voyager 2 made its closest approach to Saturn, the spacecraft's path was gravitationally altered by the ringed planet and directed toward Uranus, another billion miles away.

Now left alone to continue into uncharted territory, Voyager 2 made a somewhat shaky start toward Uranus. After the closest approach to Saturn, the steerable platform holding many of its instruments (including the cameras) became stuck. Engineers diagnosed the problem as a loss of lubricant, which soon migrated back, allowing the balky platform to move again. But new rules were created to restrict the frequency and speed of movement, preserving the ability to point the instruments during the Uranus and Neptune encounters.

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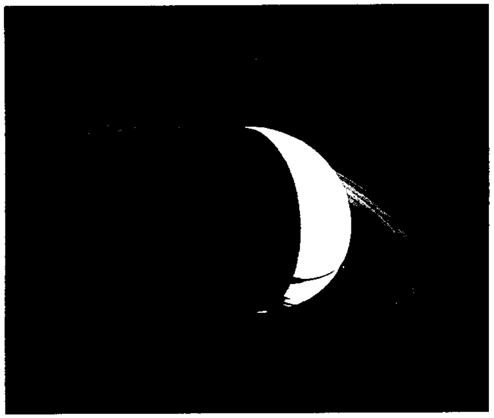


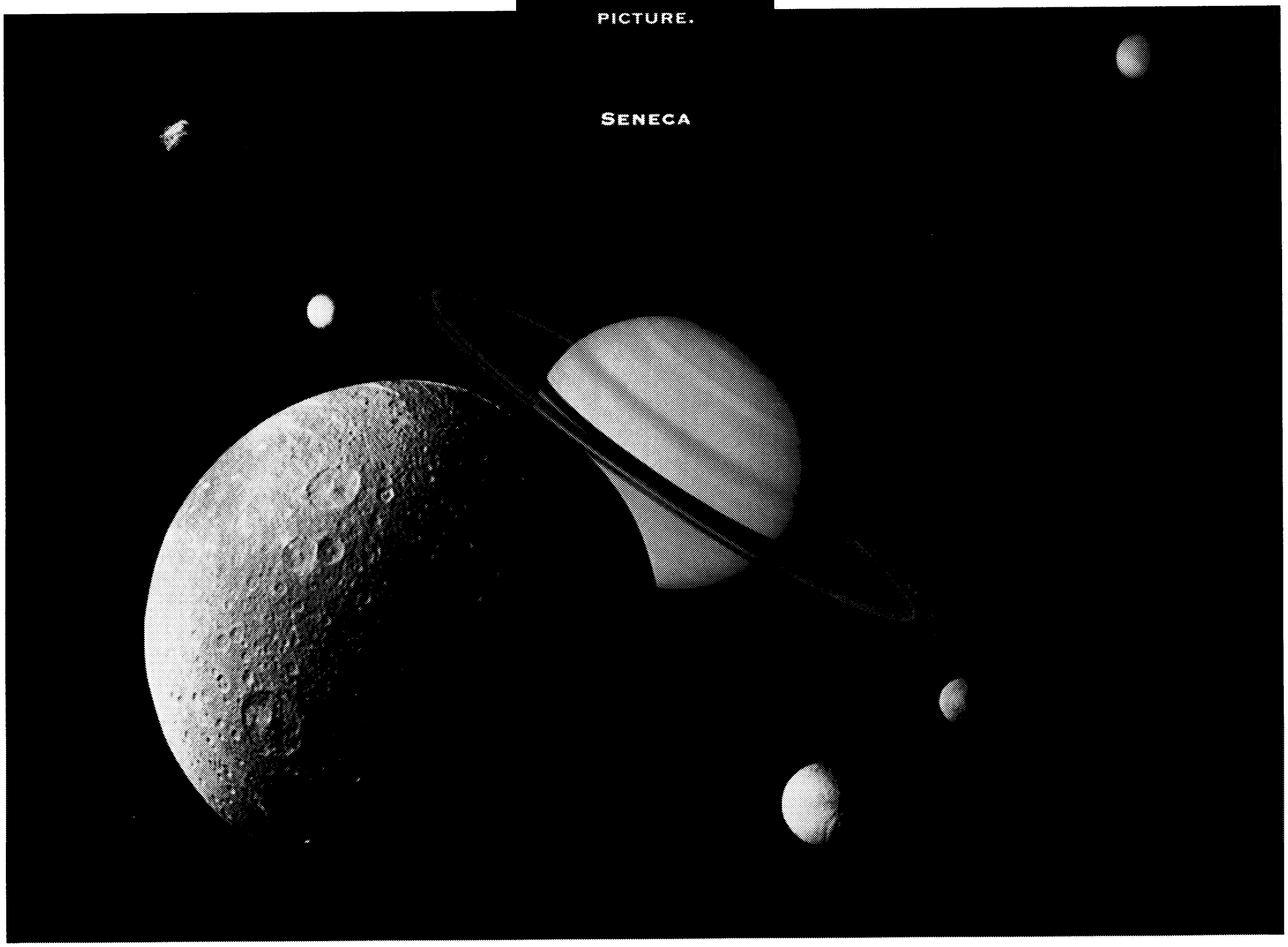
A SATURN'S SHADOW CUTS THROUGH THE PLANET'S RINGS AS VOYAGER 1 LOOKS BACK ON ITS WAY OUT OF THE SOLAR SYSTEM.

B A MONTAGE OF SATURN AND ITS MAJOR SATELLITES. CLOCKWISE FROM UPPER RIGHT ARE TITAN, MIMAS, TETHYS, DIONE, ENCELADUS AND RHEA.

SATURN'S INNER RING, THE D-RING, EXTENDS TO WITHIN 4,000 MILES OF THE PLANET'S CLOUD TOPS

THE ARTIST FINDS A GREATER PLEASURE IN PAINTING THAN IN HAVING COMPLETED THE PICTURE.

SENECA



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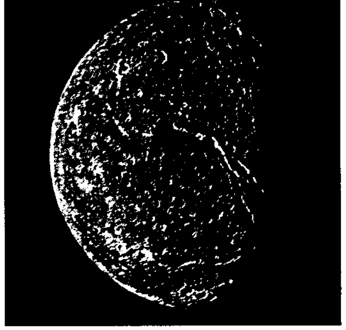


A

Uranus, the third largest planet, is known as the one that was "knocked on its side." Scientists postulate that Uranus was permanently thrown off its normal axis when it was struck by a body at least the size of Earth. As a result, the planet's poles receive more sunlight than its equatorial region. As at other planets, rings and moons orbit around the equator, giving the entire Uranian system its odd, bull's-eye appearance.

At a distance of two billion miles from Earth, Uranus is hardly an easy target of study, even through powerful telescopes. Prior to the arrival of Voyager 2, five moons had been counted, and dark rings had been detected. Only broad characteristics of the planet could be discerned. With its polar regions exposed to sunlight or darkness for long periods, scientists were not sure what to expect.

No special equipment was placed aboard Voyager 2 for its Uranus and Neptune encounters, so the spacecraft had to be taught new ways of gathering, processing and sending data to obtain the information needed at these dark and distant planets. As a spacecraft flies farther away, its signal received on Earth becomes increasingly weaker. By lowering the rate at which Voyager 2 transmitted data, engineers increased the time devoted to the transmission of each bit of data. This is akin to speaking slowly to be better understood; less is said, but what is spoken has a greater chance of being heard clearly. Since this normally would result in less data received, a new method was devised for compressing the data gathered.

New software was radioed to the spacecraft. The programming enabled one computer, a backup, to be devoted to compressing and formatting all imaging data prior to transmission. Far fewer bits were needed to rebuild a picture received from Voyager 2. The process allowed the spacecraft to return thousands, instead of hundreds, of pictures from Uranus and Neptune.

A TITANIA, THE LARGEST OF URANUS' MOONS, SHOWS LONG, DEEP FAULT VALLEYS.

B FROM A DISTANCE OF 600,000 MILES, VOYAGER 2 CAPTURED THE SUNLIT CRESCENT OF URANUS.

C MOST EVIDENCE OF EARLY CRATERING ON ARIEL HAS BEEN ERASED BY SURFACE MELTING AND OTHER ACTIVITY.

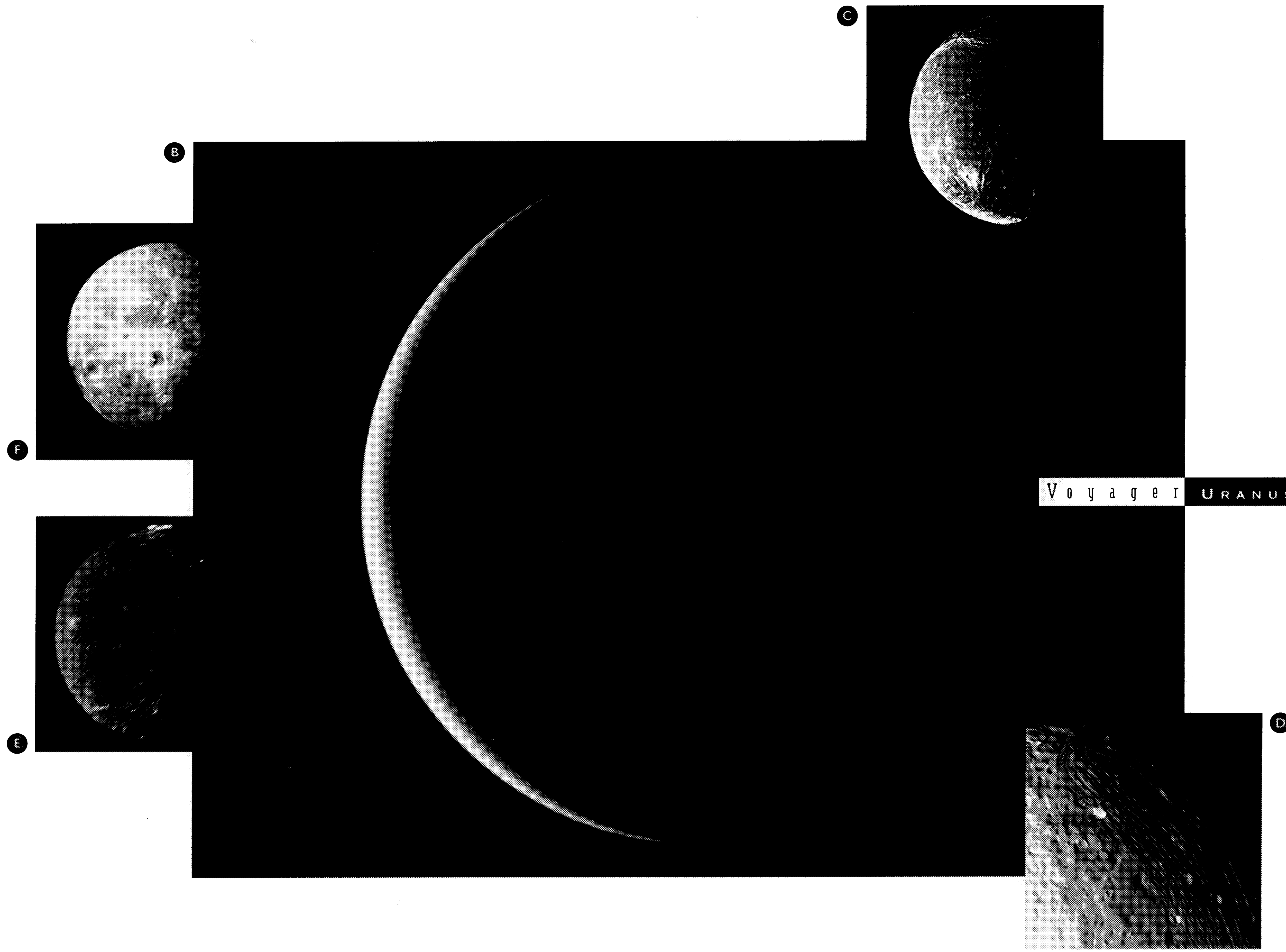
D MIRANDA MAY HAVE BEEN FROZEN IN THE MIDST OF A GEOLOGIC UPHEAVAL DURING WHICH ITS BODY WAS ALMOST LITERALLY TURNED INSIDE OUT.

E UMBRIEL IS THE DARKEST OF URANUS' LARGER MOONS, REFLECTING ONLY 2.1 PERCENT OF THE SUNLIGHT IT RECEIVES.

F OBERON'S ICY SURFACE DISPLAYS SEVERAL LARGE IMPACT CRATERS. A 13-MILE-HIGH PEAK PROTRUDES AT LOWER LEFT.

LATITUDINAL BANDING ON URANUS SHOWED THAT ROTATION DETERMINES A PLANET'S ATMOSPHERIC MOTION

Uranus



Voyager URANUS

At DSN complexes around the world, multiple antennas were electronically linked together to improve the reception of Voyager 2's faint transmissions.

High noon on Uranus is not as bright as dusk on Earth, and Voyager 2's cameras were not designed to operate at such low light levels, so new techniques were developed to allow the cameras to track their targets while making long exposures. The entire spacecraft was moved with the camera's shutter open for exposures as long as 15 seconds. This engineering feat would yield sharply focused close-ups throughout the remainder of Voyager 2's journey.

Due to the orientation of the Uranian system and Voyager 2's path through it, the spacecraft's discoveries there nearly came all at once.

A high layer of smog-like haze was found around the sunlit pole of the planet. Scientists called ultraviolet light emanating from this region "day glow." The belted latitudinal pattern seen in the atmospheres of the other giant planets is maintained on Uranus despite its orientation. A few methane clouds seen in the atmosphere revealed the presence of winds of nearly 374 miles per hour at the middle latitudes. Otherwise, the shallow hydrogen–helium atmosphere was found to be relatively inactive, with no visible hurricane-like storm systems. Voyager scientists had thought the poles would be warmer than the equatorial region, but were surprised to find that most of the planet shows nearly the same temperature at the cloud tops.

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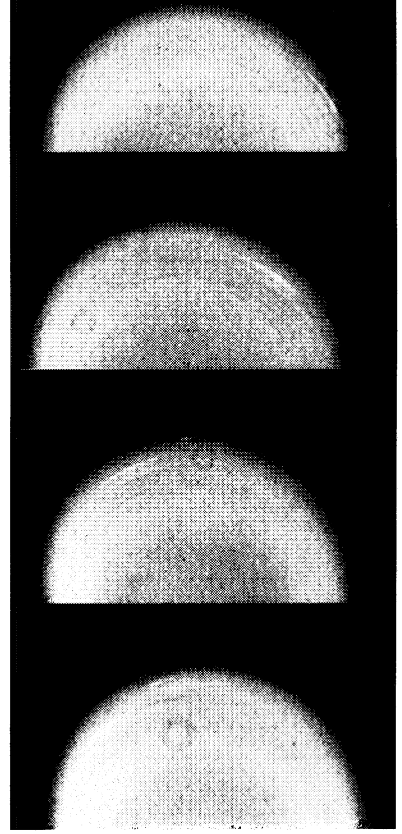


A TIME-LAPSE IMAGES SHOW CLOUDS NEAR THE LIMB MOVING COUNTERCLOCKWISE AND FASTER THAN URANUS ROTATES — BEHAVIOR EXACTLY CONTRARY TO EXPECTATIONS.

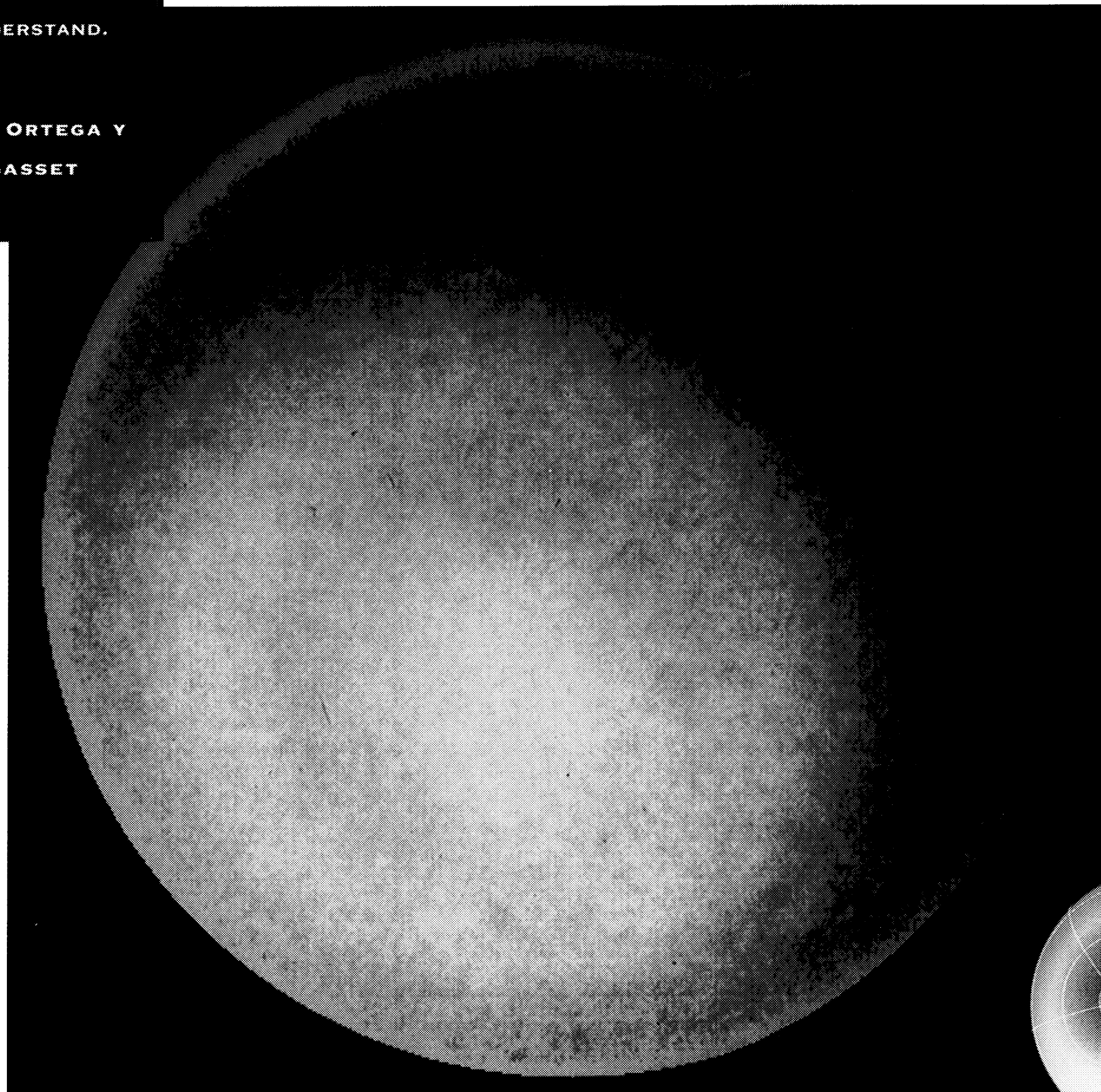
B COMPUTER ENHANCEMENT EMPHASIZES THE HIGH-LEVEL HAZE IN URANUS' UPPER ATMOSPHERE. CLOUDS ARE OBSCURED BY THE OVERLYING ATMOSPHERE.

C A LATITUDE–LONGITUDE GRID SUPERIMPOSED ON A COMBINATION IMAGE SHOWS THAT URANUS' ATMOSPHERE CIRCULATES IN THE SAME DIRECTION AS THE PLANET ROTATES.

EACH OF URANUS' POLES IS IN SUNLIGHT FOR 42 YEARS (AS IT GOES FROM DAWN TO DUSK)

To be surprised, to wonder, is to begin to understand.

José Ortega y Gasset



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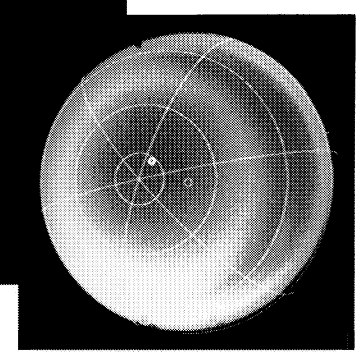


C

Voyager 2's closest approach to Uranus on January 24, 1986, also brought the spacecraft near a little moon called Miranda. It would be the closest satellite flyby of the encounter with Uranus, but the Voyager team had no way of knowing in advance if Miranda would be of particular interest or pale in comparison to other, less accessible Uranian moons. Nevertheless, a series of close-ups of the moon was planned. Fortunately for planetary scientists, Miranda was the scientific equivalent of pay dirt.

The smallest of the five Uranian moons known before Voyager 2, Miranda seems too diminutive and cold to possess the diverse geologic features it has. Giant faults have sliced canyons as deep as 12 miles into the surface. Rolling plains that are heavily cratered abut large patches of grooved and ridged terrain. These characteristics suggest Miranda may have undergone strong tidal heating in the

URANUS HAS A VIRTUALLY UNIFORM TEMPERATURE OF −353 DEGREES FAHRENHEIT

past, possibly during a time when the small moon occupied a chaotic orbit around Uranus. Whatever forces shaped Miranda, they seem to have stopped. Planetary scientists have theorized that Miranda was frozen in the midst of a geologic process that most terrestrial (solid, Earth-like) bodies are thought to have undergone at an early age, a process in which the body almost literally turns inside out. Still other theories put forth that Miranda is the reaggregated sum of the parts of one or more moons that shattered in a collision with a comet.

The other large Uranian moons display the same variety found in Jupiter's and Saturn's collections. Ariel and Titania both have valleys formed by faults. Titania has fault lines that may be the result of the expansion of subsurface water as the moon's interior froze. Oberon and Umbriel have old surfaces little changed since their formation. Umbriel's surface is darker than those of its companions and may have been blanketed by a layer of dark debris. Any methane in its icy crust would have been darkened from the continual bombardment by ions trapped in the Uranian magnetic field.

(A) A 140-MILE-WIDE PATCH OF MIRANDA'S SURFACE SHOWS EVIDENCE OF A VARIETY OF GEOLOGIC PROCESSES.

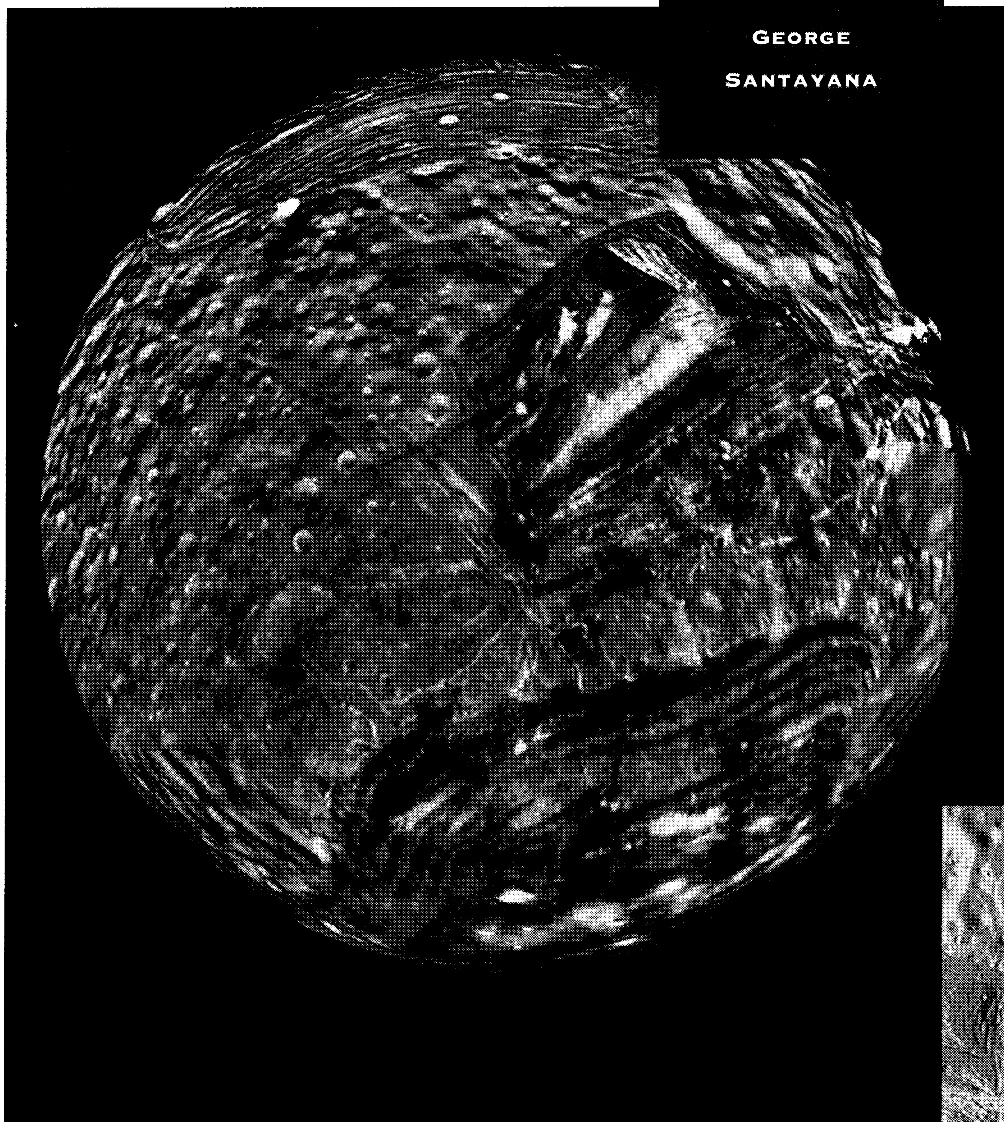
(B) THIS NINE-IMAGE MOSAIC OF MIRANDA SHOWS OLD, HEAVILY CRATERED AREAS AND YOUNG, COMPLEX REGIONS WITH SCARPS AND RIDGES.

(C) A FALSE-COLOR VERSION OF PHOTOGRAPH "A" HIGHLIGHTS THE TORTUOUS CHANGES MIRANDA HAS UNDERGONE.

I HAVE IMAGINATION, AND NOTHING THAT IS REAL IS ALIEN TO ME.

GEORGE SANTAYANA

B



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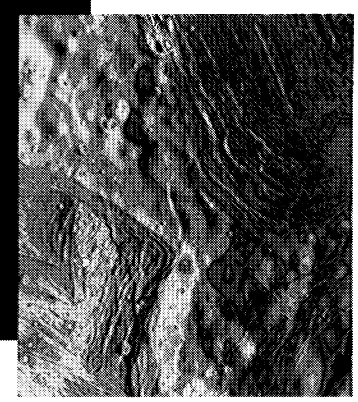

Ten new moons were found orbiting near the rings, bringing the total to 15. Based on the knowledge gained at Saturn, scientists predicted and found shepherding moons ushering the outermost of Uranus' rings; the moons herding other rings may have been too dark or tiny for Voyager 2's cameras to record.

Voyager 2 counted two new Uranian rings in addition to the nine that were already known. From the Uranian rings, scientists have determined that planetary rings may be short-lived phenomena that come and go throughout a planet's lifetime. The particles in orbit around Uranus are thought to be pieces of a moon that broke up; the rings contain relatively little dust, in contrast to Saturn's E- and F-rings and Jupiter's ring. It is thought that atmospheric drag, due to the hydrogen corona that Voyager 2 observed around Uranus, causes dust particles to spiral into the planet. In time, the rings may vanish. New rings would form only with the breakup of another moon or a captured meteoroid or comet.

Perhaps the weirdest aspect of the Uranian system is its magnetic field. On other planets, including Earth, the axis of the magnetic field is nearly parallel to the axis of rotation, placing the magnetic poles near the geographic poles. But Uranus' magnetic axis is tilted about 59 degrees and offset from the center of the planet by 30 percent of its radius (4,500 miles), placing the magnetic poles nearer the equator. As it rotates with the planet, the field is forced back by the wind of charged particles from the Sun and wound into a twisting magnetotail. Scientists believe the field is generated at an intermediate depth in the planet's interior — where the pressure is high enough for water to become electrically conductive.

Radiation belts at Uranus were found to be of an intensity similar to those at Saturn; irradiation would quickly darken (within 100,000 years) any methane trapped in the icy surfaces of the inner moons and ring particles. This may account for the darkened surfaces of the moons and ring particles.

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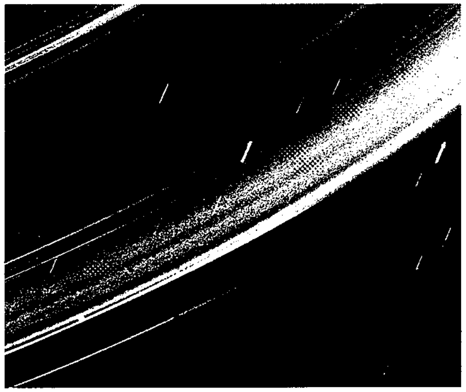


A SMEARED IMAGES OF BACKGROUND STARS ARE VISIBLE THROUGH THE RINGS OF URANUS IN THIS 96-SECOND, WIDE-ANGLE EXPOSURE.

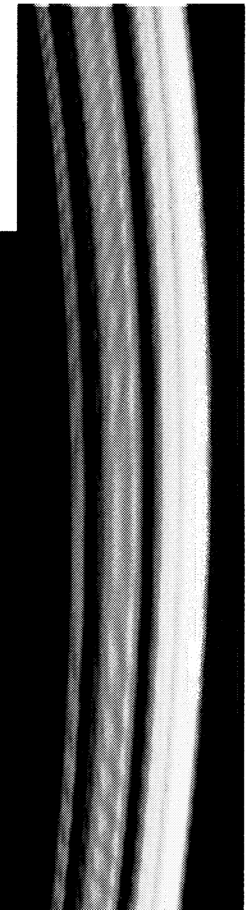
B URANUS' FAR-FLUNG RINGS, PHOTOGRAPHED BY VOYAGER 2 AS IT APPROACHED THE PLANE OF THE URANIAN RING SYSTEM.

C VOYAGER 2'S PHOTOPOLARIMETER RECORDED THE DATA FOR THIS FALSE-COLOR PICTURE AS THE STAR SIGMA SAGITARII PASSED BEHIND URANUS' DELTA RING.

D THE URANIAN MAGNETIC FIELD'S TILTED AXIS CAUSES THE MAGNETIC TAIL TO TWIST BEHIND THE PLANET.

B

C



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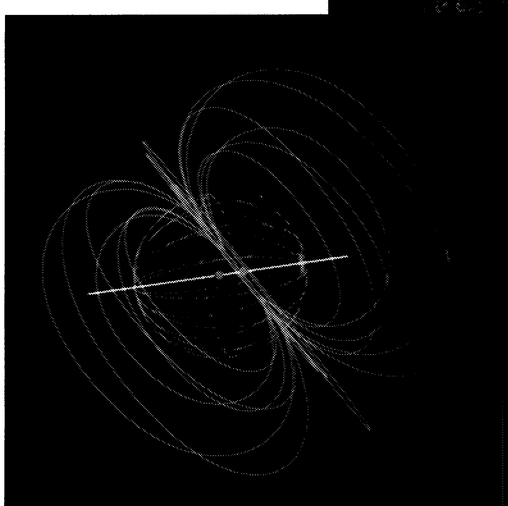

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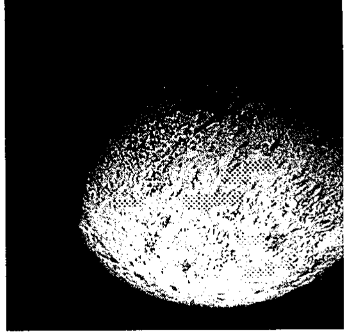


A billion and a half miles beyond Uranus was Neptune — and Voyager 2's last encounter with a planet. At the time of Voyager 2's flyby, Neptune was the most distant member of the solar system. (Pluto once again will become most distant in 1999.) The astonishing discoveries made by the spacecraft at Neptune and its moon Triton would make the final flyby the pièce de résistance of the Voyager mission.

Orbiting at the edge of the solar system, Neptune is the smallest of the solar system's giant planets. Very little was known about it before Voyager 2's arrival on August 25, 1989, so nearly everything the spacecraft observed was new.

Because Neptune receives so little sunlight (only 3 percent of Jupiter's total), it was expected to be somewhat less active than the other giant planets. Yet Neptune's atmosphere showed itself to be surprisingly dynamic, with winds blowing westward, opposite the direction of rotation, at more than 1,200 miles an hour — faster than winds on any other planet. Neptune's winds are not very turbulent, so less energy is needed to maintain their high speeds.

Early in Voyager 2's approach, a giant storm the size of Earth peered out from Neptune's atmosphere like a giant eye. Called the Great Dark Spot, it resembles Jupiter's Great Red Spot, with winds blowing counterclockwise and moving westward at almost 745 miles per hour. A small, irregularly shaped, eastward-moving cloud was seen darting around Neptune every 16 hours or so. This "scooter," as Voyager scientists called it, may be the top of a cloud plume rising above a deeper cloud deck. Long, bright clouds similar to cirrus clouds on Earth were seen casting their shadows on lower level clouds in the atmosphere.

A Regions highly reflective in the ultraviolet appear blue in this picture of Neptune's moon Triton taken through green, violet and ultraviolet filters.

B Neptune's haze appears in false color as a red rim. White clouds and a circular storm form as hydrocarbon gases condense into brighter areas.

C Images taken during successive rotations of the planet show changes in the clouds around Neptune's Great Dark Spot.

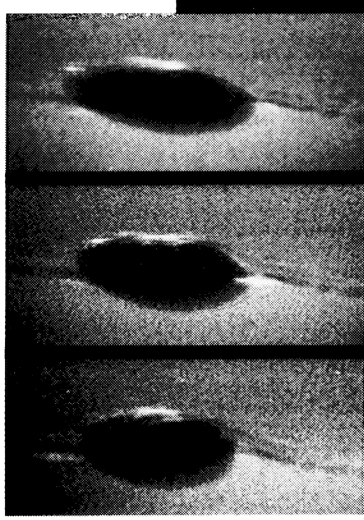
Neptune's interior thermal energy exceeds what it absorbs from the Sun by a factor of 1.7

’Tis distance lends enchantment to the view, and robes the mountain in its azure hue.

Thomas Campbell

B

C



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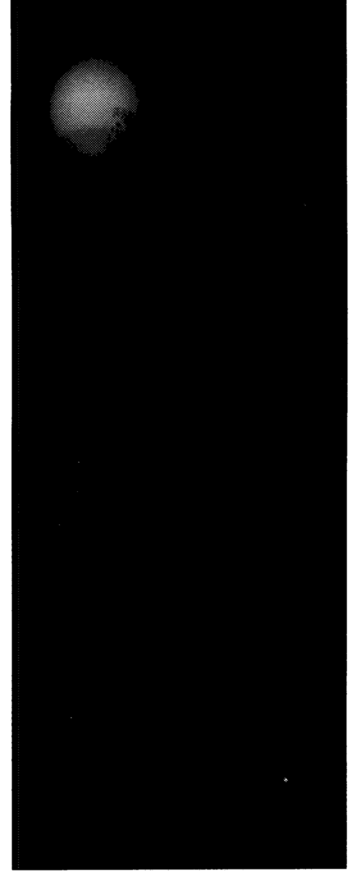


Before Neptune's magnetic field was measured, scientists believed Uranus' to be unique in its huge offset from the planet's axis of rotation. But Neptune's field turned out to be highly tilted too — 47 degrees from the rotational axis and offset at least 0.55 radius (about 8,500 miles) from the physical center of the planet. Comparing the two magnetic fields, scientists think that the unusual orientations may be characteristic of flows in the interior of both Uranus and Neptune — and not the result of magnetic field reversals, or, in Uranus' case, of the planet being tipped on its side.

Like its sibling giant planets, Neptune was found to be completely encircled by rings rather than surrounded by the partial rings or "ring arcs" that had been detected from Earth. Some of its rings are diffuse, dusty sheets; others have unevenly spaced clumps of dense material. These concentrations of ring material are puzzling; the material should have spread uniformly throughout a particular ring in just a few years.

Two moons, Nereid and Triton, were known to orbit Neptune, but Voyager 2 found six more. The new moons are all very dark and small, ranging from 30 to 250 miles in diameter. Like the rings, the smallest of these are probably fragments of larger, shattered moons.

Voyager 2's close look at Triton did not disappoint a science team that had learned to expect surprises. This large moon, which has a thin atmosphere of nitrogen and methane, is the coldest object in the solar system, with a temperature of –391 degrees Fahrenheit. Still, it possesses a remarkable range of activity, including geyser-like plumes. These eruptions carry dark hydrocarbons upwards several miles, where they are blown away in high winds.

A NEPTUNE AND ITS LARGEST SATELLITE, TRITON (LOWER RIGHT), SEEN THROUGH VIOLET, CLEAR AND ORANGE FILTERS.

B IN NEPTUNE'S OUTERMOST RING, 39,000 MILES OUT, MATERIAL MYSTERIOUSLY CLUMPS INTO THREE ARCS.

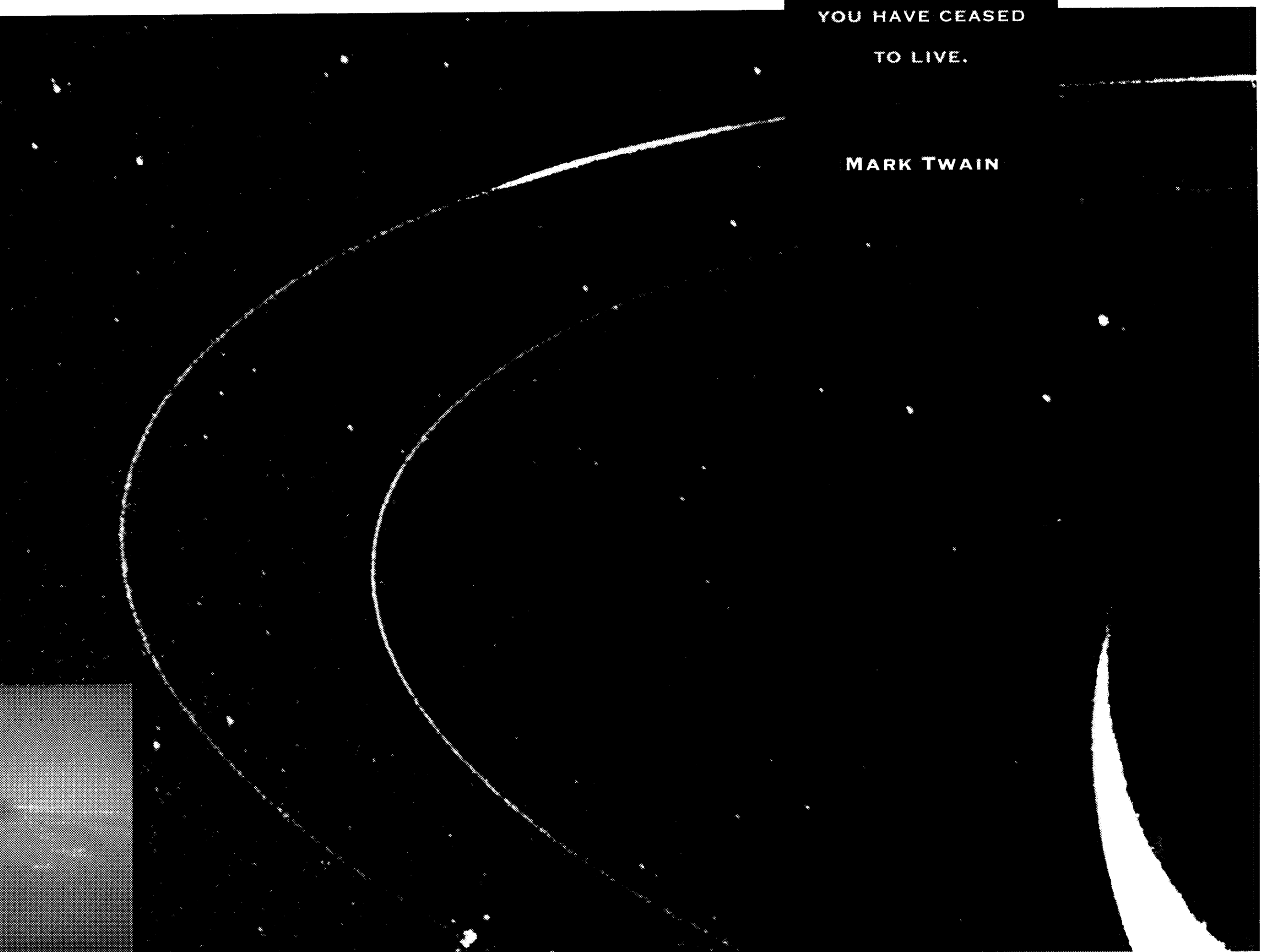
C MOVING EASTWARD AT DIFFERENT VELOCITIES, NEPTUNE'S GREAT DARK SPOT (TOP), "SCOOTER" (MIDDLE) AND DARK SPOT 2 (BOTTOM) ARE RARELY SEEN TOGETHER.

THE FREQUENCY OF NEPTUNE'S RADIO SIGNALS INDICATED ITS ROTATION PERIOD — 16 HOURS 7 MINUTES

DON'T PART WITH YOUR ILLUSIONS. WHEN THEY ARE GONE, YOU MAY STILL EXIST BUT YOU HAVE CEASED TO LIVE.

MARK TWAIN

B



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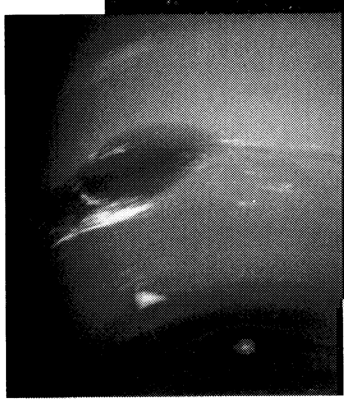

Triton's relatively high density and its retrograde orbit (opposite to the direction of Neptune's rotation) indicate that the satellite is not an original member of the Neptune system, but is a captured object. If that is the case, tidal heating could have melted Triton during the time it had a more eccentric orbit. The moon might have been molten for as long as a billion years.

Fault valleys crisscross Triton's frozen, water-ice surface near the equator. The faults are filled by ridges of ice extruded from the interior. The volcanic craters have been repeatedly flooded and refrozen, forming bright, lake-like features.

Neptune's radiation belts encompass Triton, possibly producing the pink and reddish hues on the moon's surface by irradiation. Fine-grained frost on Triton's surface appears blue.

Some of the charged particles traveling along Neptune's magnetic field lines strike Triton's atmosphere, exciting atoms there and producing an auroral glow detected by Voyager 2's ultraviolet spectrometer. Triton and Saturn's Titan are among the few satellites in the solar system to have atmospheres, and the only two moons known to have auroras.

Pluto may remain unexplored, but Triton gave scientists a glimpse of what to expect from that planet. Triton and Pluto share many characteristics: they are about the same size and have thin atmospheres. Both are about three-quarters rock and one-quarter ice; each has a layer of methane ice at its surface. Given these similarities, planetary scientists recognize that Voyager 2's flyby of Triton provided the best look we may have of Pluto for a long time.

With the planetary phase of its long mission accomplished, Voyager 2 took a sharp dive past Neptune, heading southward into a course that eventually will take the spacecraft out of the solar system.

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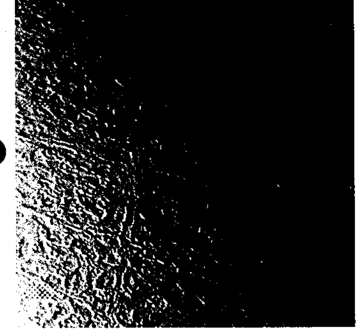

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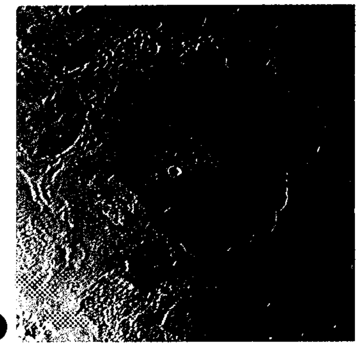


A LONG, NARROW FAULTS ABOUT 20 MILES ACROSS ARE VISIBLE IN THIS IMAGE OF TRITON.

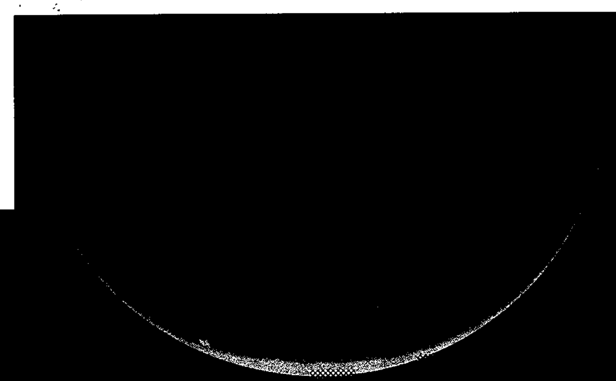
B THIS VIEW OF AN AREA ON TRITON ABOUT 300 MILES ACROSS SHOWS A LARGE, ICY BASIN.

C A DOZEN IMAGES WERE COMBINED TO PRODUCE THIS COMPREHENSIVE VIEW OF THE NEPTUNE-FACING HEMISPHERE OF TRITON.

D VOYAGER 2'S POST-ENCOUNTER VIEW OF NEPTUNE'S SOUTH POLE AS THE SPACECRAFT SPED AWAY ON A SOUTHWARD TRAJECTORY.

A SEASONAL ICE CAP OF NITROGEN AND METHANE COVERS MUCH OF TRITON'S SOUTHERN HEMISPHERE

D



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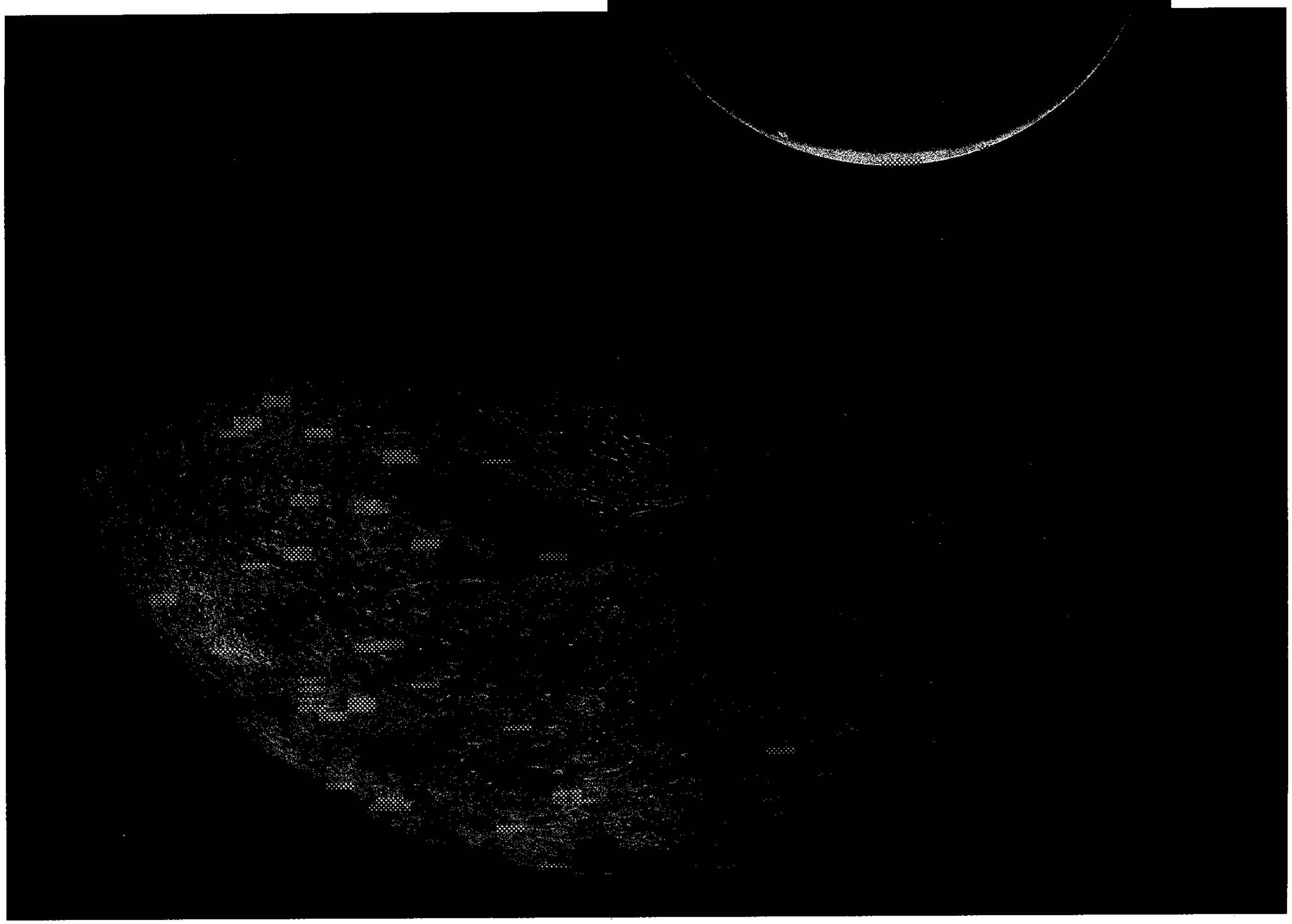

Neptune

I THINK
THESE DIFFICULT
TIMES HAVE
HELPED ME
TO UNDERSTAND
BETTER THAN
BEFORE
HOW INFINITELY
RICH AND
BEAUTIFUL LIFE
IS IN EVERY WAY,
AND THAT SO
MANY THINGS
THAT ONE GOES
AROUND
WORRYING ABOUT
ARE OF NO
IMPORTANCE
WHATSOEVER.

ISAK DINESEN

Both Voyagers are headed toward the outer boundary of the solar system in search of the heliopause, the region where the Sun's influence wanes and the beginning of interstellar space can be sensed. The heliopause has never been reached by any spacecraft; the Voyagers may be the first to pass through this region, which is thought to exist somewhere from 5 to 14 billion miles from the Sun. Sometime in the next 10 years, the two spacecraft should cross an area known as the termination shock. This is where the million-mile-per-hour solar wind slows to about 250,000 miles per hour — the first indication that the wind is nearing the heliopause. The Voyagers should cross the heliopause 10 to 20 years after reaching the termination shock.

The Voyagers have enough electrical power and thruster fuel to operate at least until 2015. By that time, Voyager 1 will be 12.4 billion miles from the Sun and Voyager 2 will be 10.5 billion miles away.

Eventually, the Voyagers will pass other stars. In about 40,000 years, Voyager 1 will drift within 1.6 light years (9.3 trillion miles) of AC+79 3888, a star in the constellation of Camelopardalis. In some 296,000 years, Voyager 2 will pass Sirius, the brightest star in our sky, at a distance of about 4.3 light years (25 trillion miles). The Voyagers are destined — perhaps eternally — to wander the Milky Way.

FACING PAGE: VOYAGER 1 PHOTOGRAPHED EARTH – A TINY, WHITE SPECK – FROM NEARLY FOUR BILLION MILES AWAY IN FEBRUARY 1990. THE SURROUNDING STREAK IS A REFLECTION FROM SUNLIGHT STRIKING THE CAMERA'S OPTICAL SYSTEM.

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