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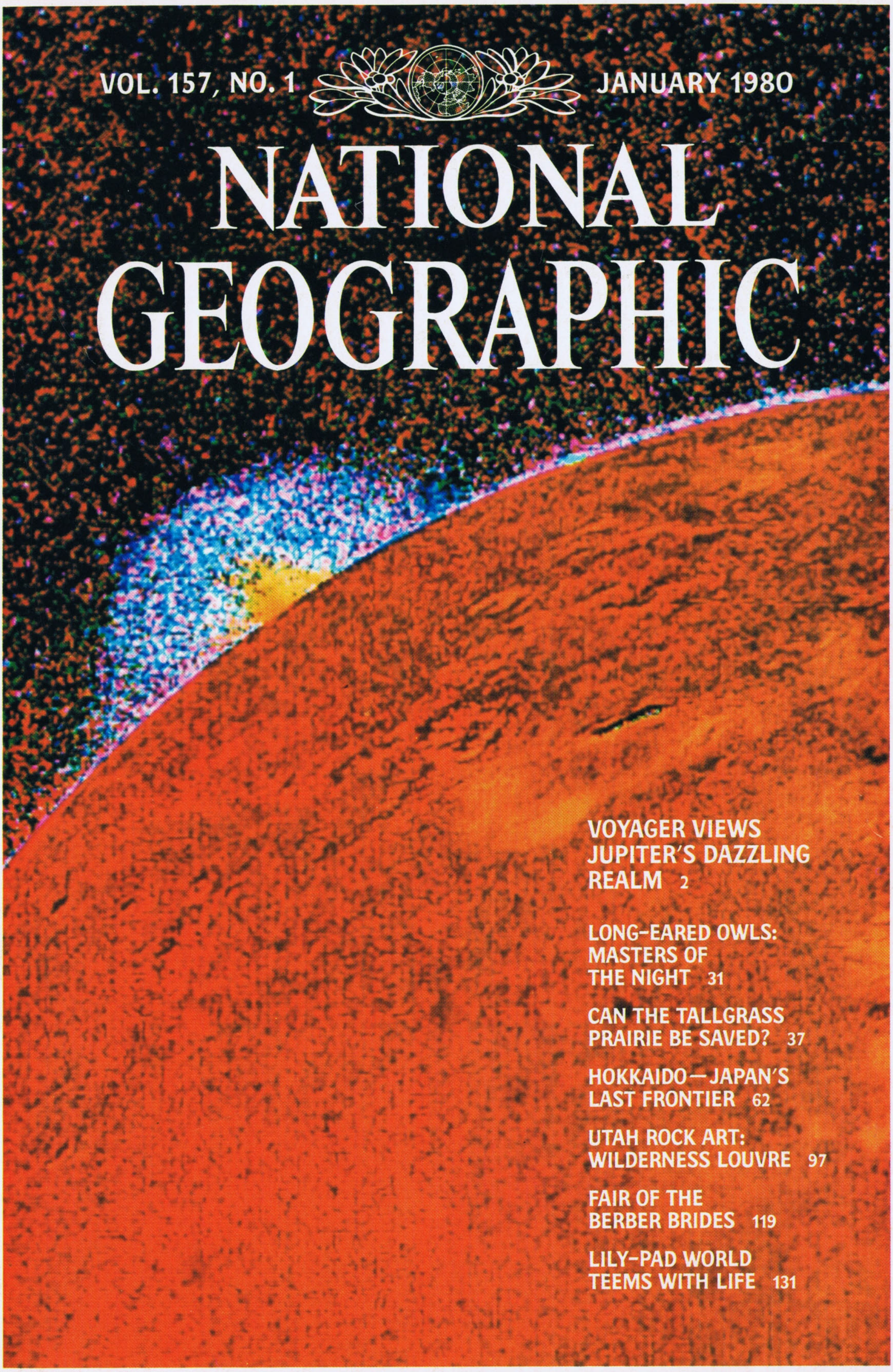

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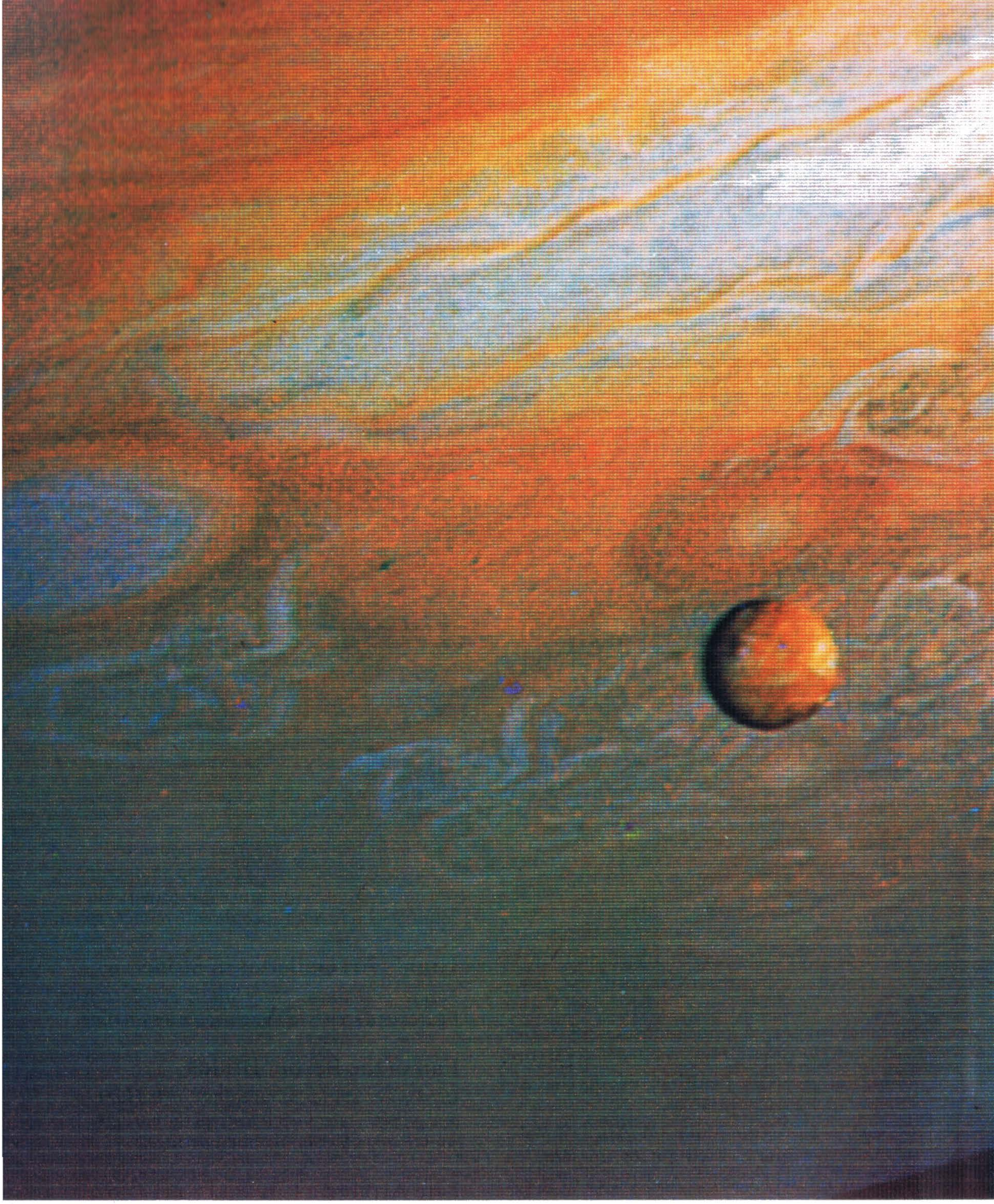
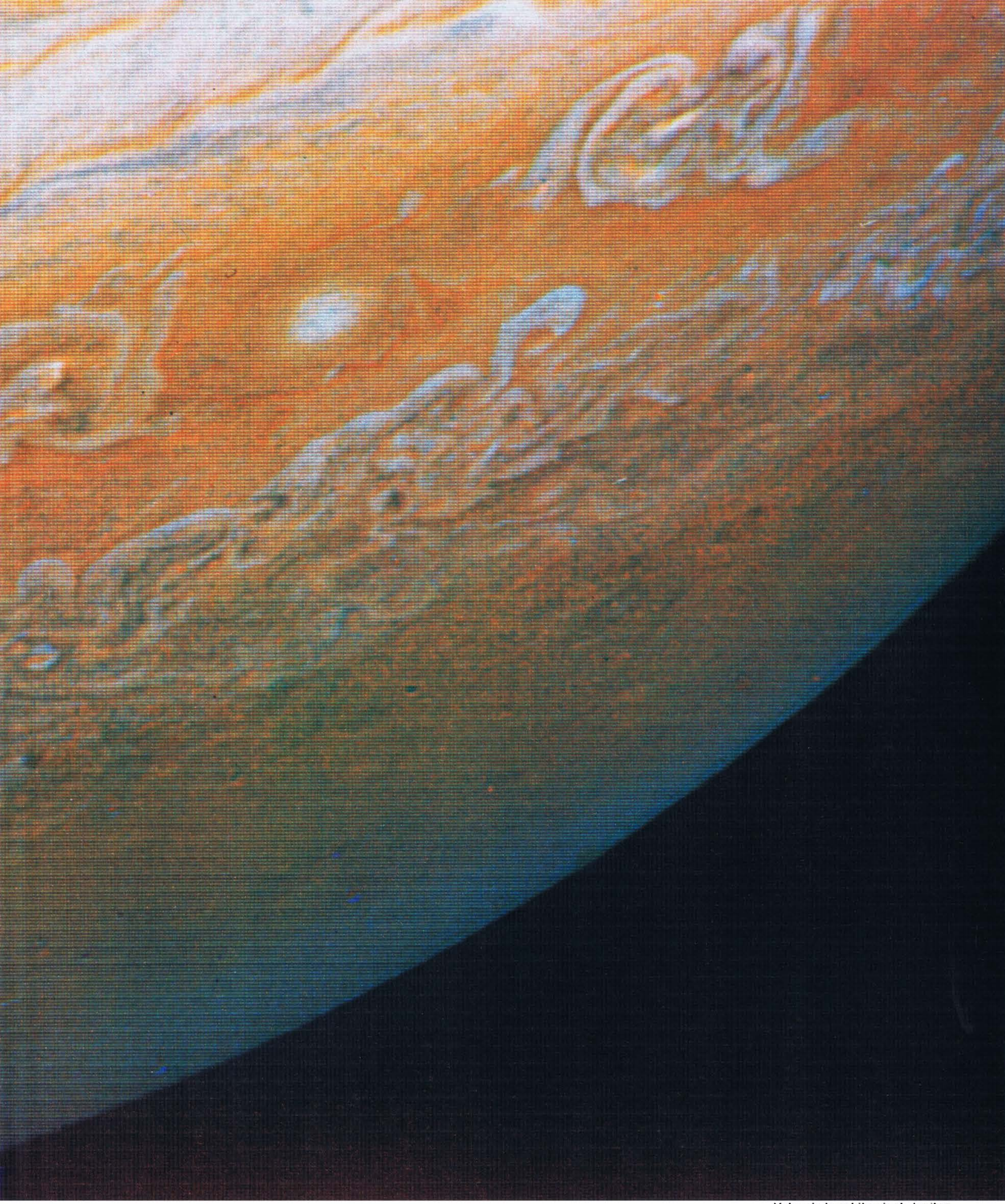


What Voyager Saw: Jupiter's

By RICK GORE NATIONAL GEOGRAPHIC SENIOR STAFF

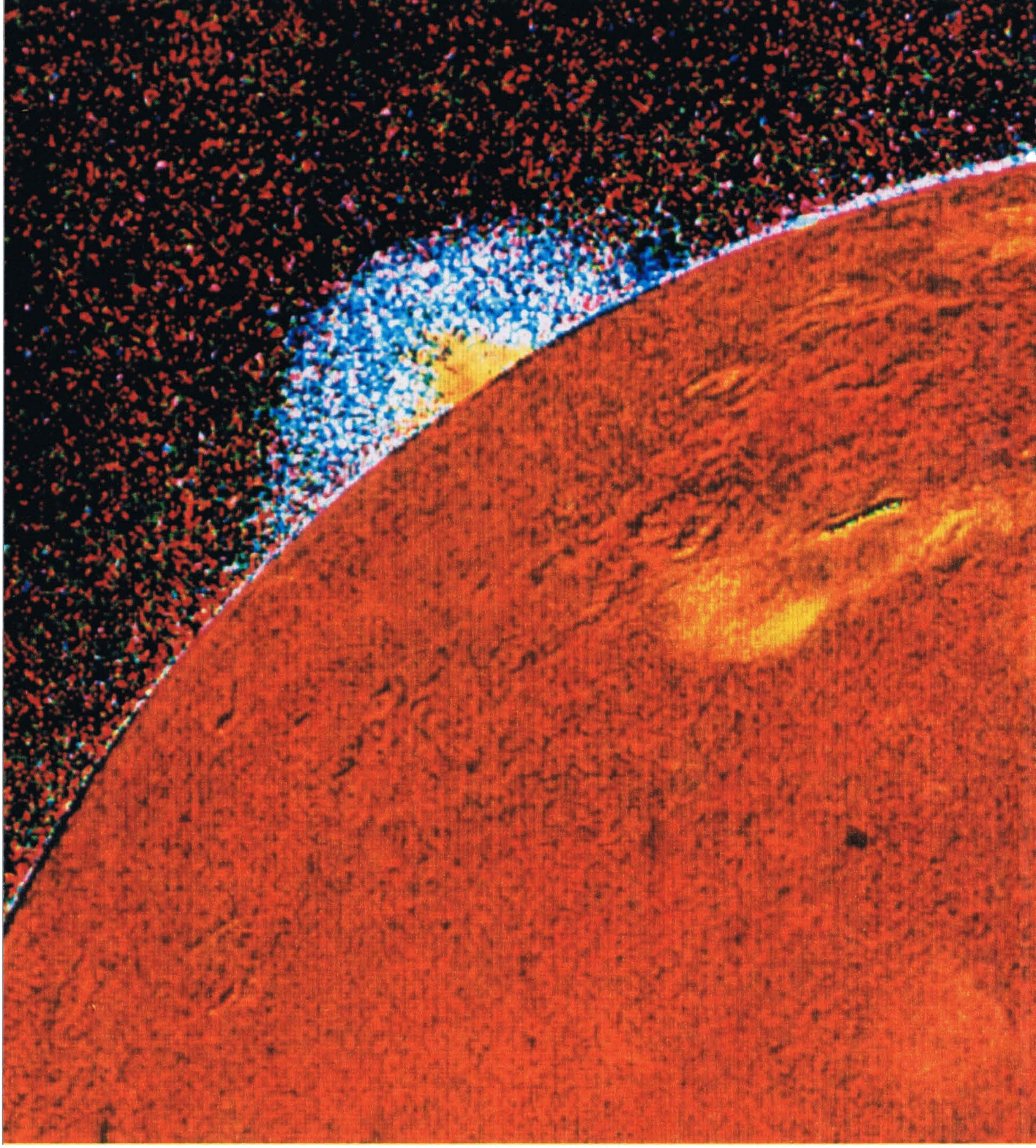


Volcanic Io orbits giant Jupiter

Dazzling Realm

Photographs by NASA

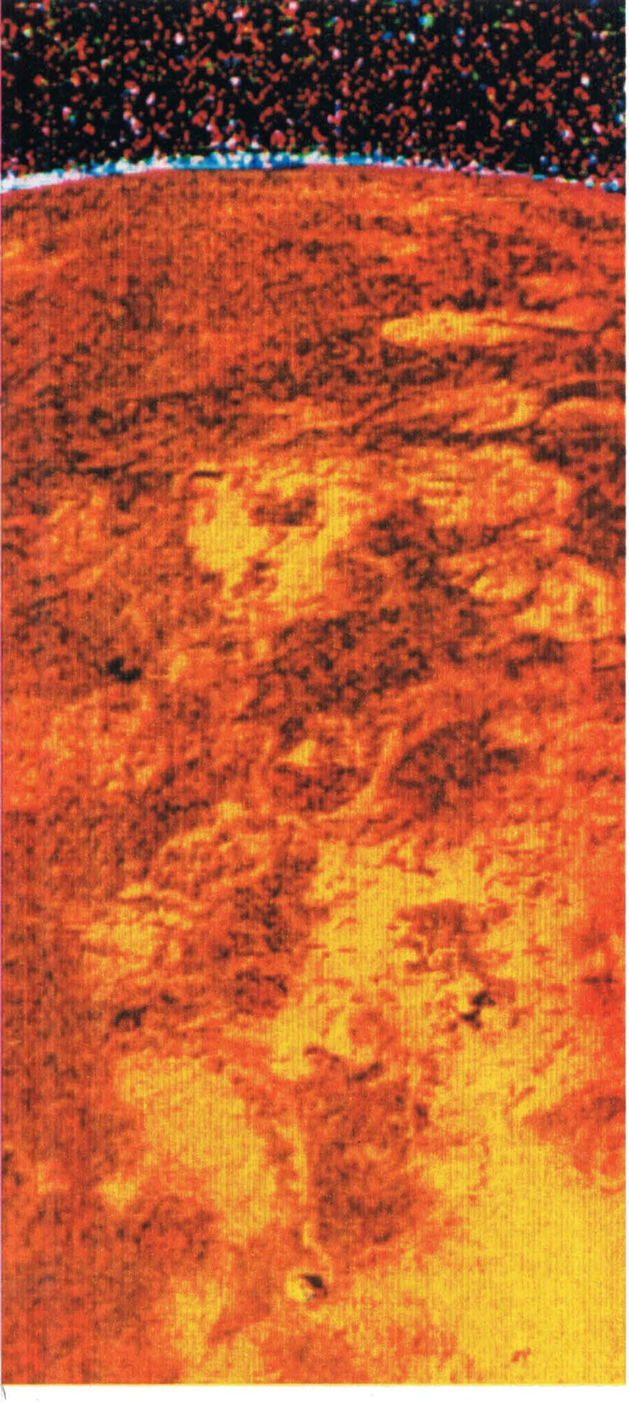
Two small spacecraft find worlds so bizarre and unexpected that at first scientists could only shout like seamen making landfall at an undreamed of archipelago



THE EXCITEMENT was subsiding at the Jet Propulsion Laboratory on Friday, March 9, when Linda Morabito made her discovery. Most members of the Voyager imaging team, exhausted by days and nights of nonstop encounter with Jupiter and its moons, were taking a long weekend off. But Morabito, one of the unsung navigation engineers who had steered Voyager 1 on its picture-taking flight past Jupiter, was at work.

Jupiter's gravity field had already flung Voyager 1 off toward Saturn for a late 1980 rendezvous. Now Morabito was doing a low-priority, post-flyby check on the orbits of Jupiter's moons.

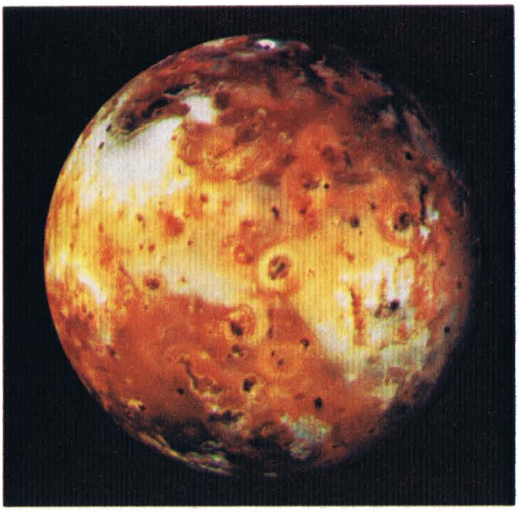
Her team steers by the stars. She sat at a computerized imaging module and called up onto its screen a picture that Voyager 1 had taken looking back at Jupiter's odd moon Io. Near Io she expected to find a star named AGK3-10021. Its exact location relative to Io



*SULFUROUS FOUNTAIN leaps up against the black of space from the limb of Io, Jupiter's innermost large moon (**left,** shown in false color).*

*Scientists had deduced that surface pocks (**bottom**) were volcanic calderas, some larger than any on earth. Engineer Linda Morabito (**below**), while doing routine navigation checks, spotted a plume rising 280 kilometers (174 miles)—first evidence of active volcanism beyond earth.*

ALBERT MOLDVAY

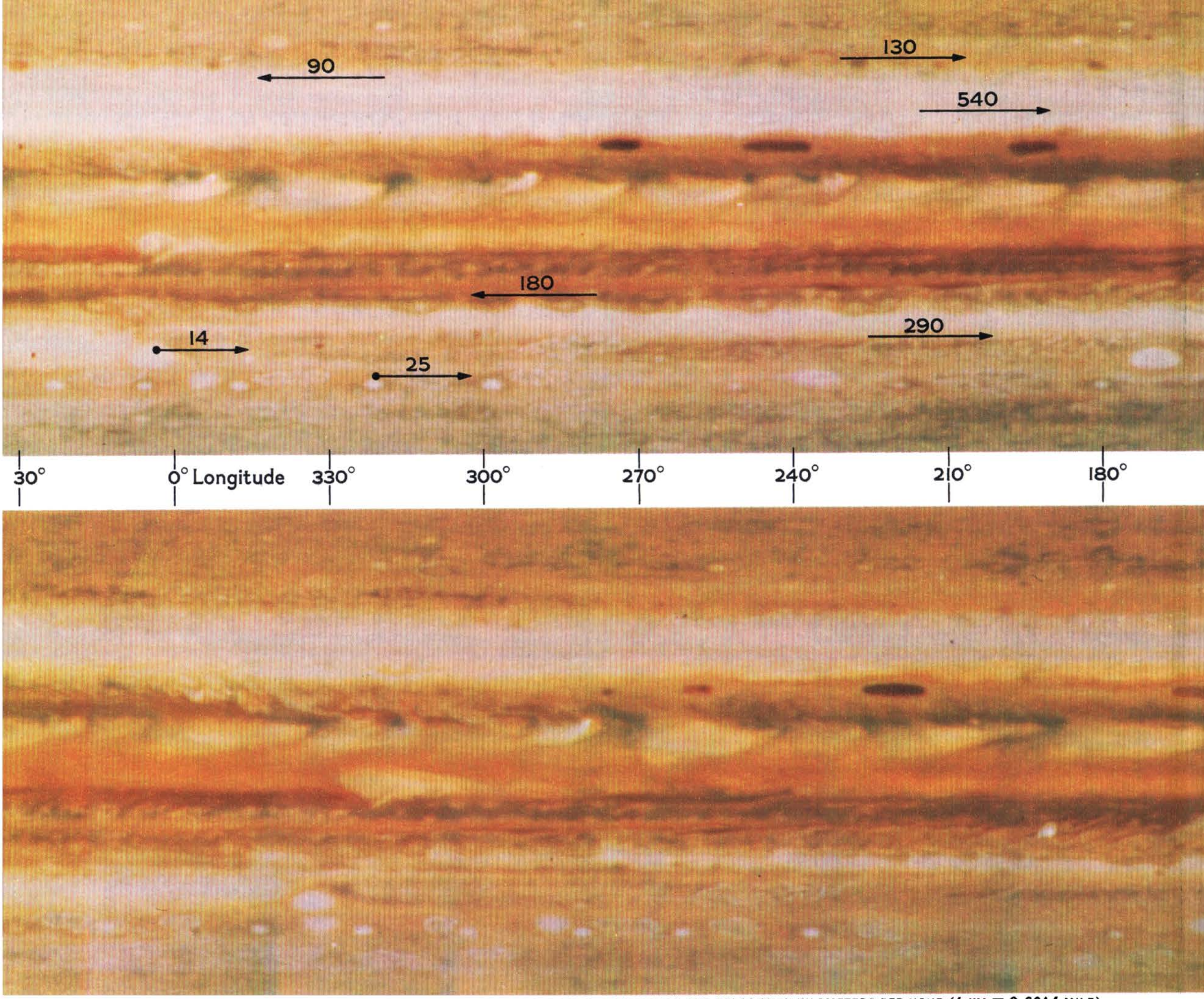


would help them calculate the moon's orbit more precisely. AGK3-10021 is a faint star, so Morabito used her computer to exaggerate its brightness on her screen. As she did, a great umbrella-shaped plume also emerged on the edge of Io.

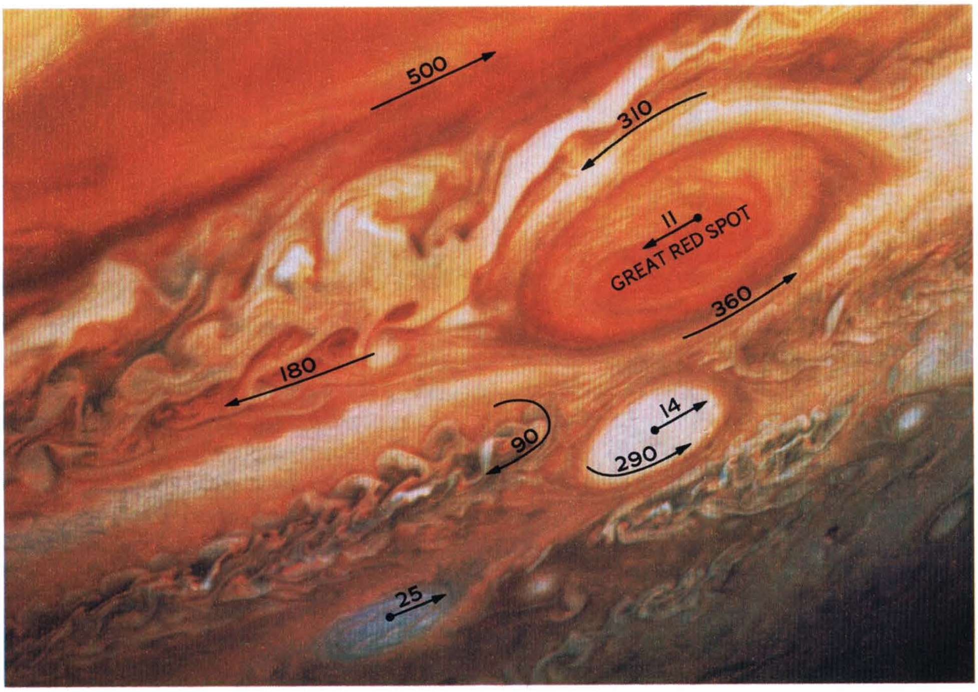
"I'd never seen anything like this before—and I suspected no one else had either," she recalled.

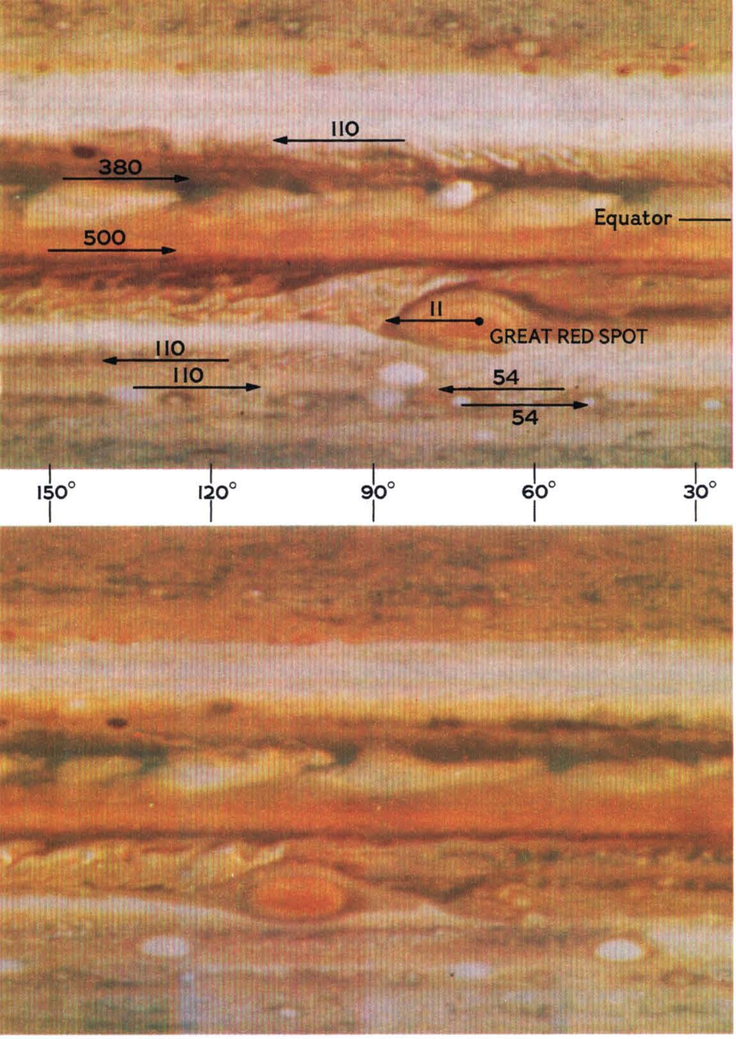
Indeed, not since Galileo saw four moons circling Jupiter in 1610 had anyone seen such a remarkable sight in Jupiter's realm. Voyager had found a volcano erupting, its plume rising 280 kilometers (174 miles).

Morabito knew that an active volcano on Io could be the greatest find of the planetary exploration program. It would mean that some other world in our solar system is still geologically alive. So she and her colleagues checked and rechecked the picture before taking her discovery to the imaging team. By Monday *(Continued on page 11)*



ARROWS AND NUMBERS INDICATE CLOUD DIRECTION AND VELOCITY IN KILOMETERS PER HOUR (1 KM = 0.6214 MILE)
VELOCITY DATA BY RETA F. BEEBE, NEW MEXICO STATE UNIVERSITY





JUPITER, UNROLLED in two views taken four months apart by Voyagers 1 and 2 and aligned by longitude **(left)***, shows changes in the bright zones and dark belts of the planet's atmosphere. Most evident are the 30-degree westward migration of the Great Red Spot in the southern hemisphere and the changed positions of the white ovals beneath it. Numbered arrows show velocities and directions of clouds, including those in the turbulent Great Red Spot region* **(lower left)***.*

Near the equator, a row of white horsetail clouds, somewhat dissipated after four months, releases heat from below by convection. Their regular spacing, as with the small white ovals, may be caused by waves in the rapidly rotating planet's atmosphere.

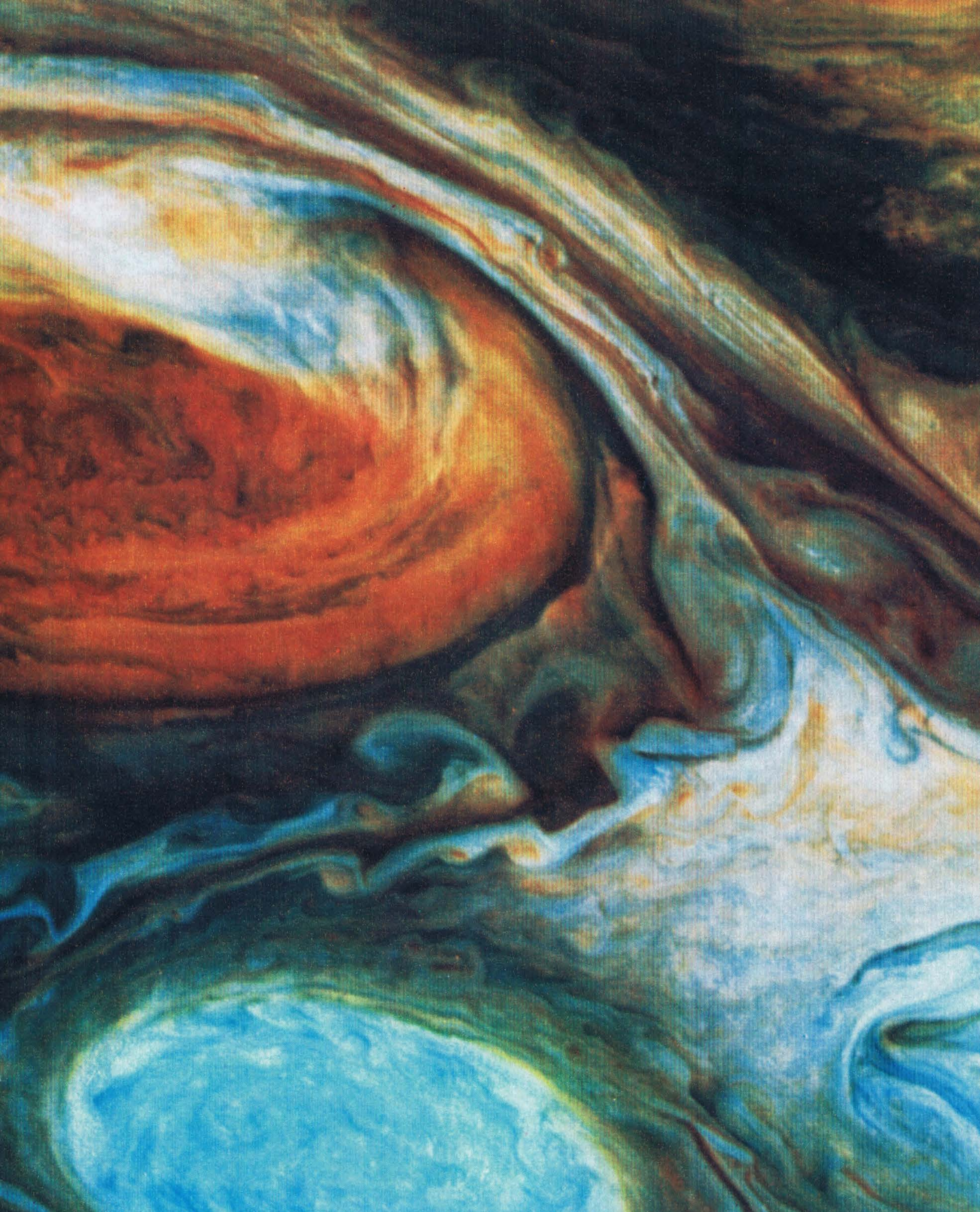
Jupiter's atmosphere may have flow patterns more predictable than those of earth's, but its chemistry is more complex. Depending on temperature and pressure, cloud decks of different chemical composition, interlayered with transparent hydrogen and helium gas **(diagram)** *form a sandwich a hundred kilometers thick. Whereas earth has only one zone of weather, the troposphere, based on the evaporation, condensation, and precipitation of water, Jupiter has three: one of water, one of ammonium hydrosulfide, and one of ammonia. Below the atmosphere, the planet is mainly liquid hydrogen and helium. It has no solid surface.*

NATIONAL GEOGRAPHIC ART DIVISION

A Jupiter movie

Scientists studying movements in the atmosphere of Jupiter employ time-lapse still photography converted to a movie. To approximate that effect, hold the magazine closed and flip the lower right-hand corner back to front with your left thumb so that the small images of the planet appear to show motion. ▶

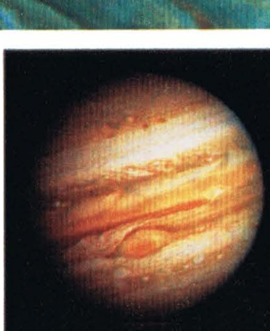
*WEATHER of the violent Jovian sort, the immense high-pressure area called the Great Red Spot swirls in a view enhanced in red and blue to emphasize detail. Its true color (**right**) may be due to traces of phosphorus or organic molecules being transported from below. The spot has been seen by telescope for at least a century and possibly three. And although it has been shrinking, the spot*

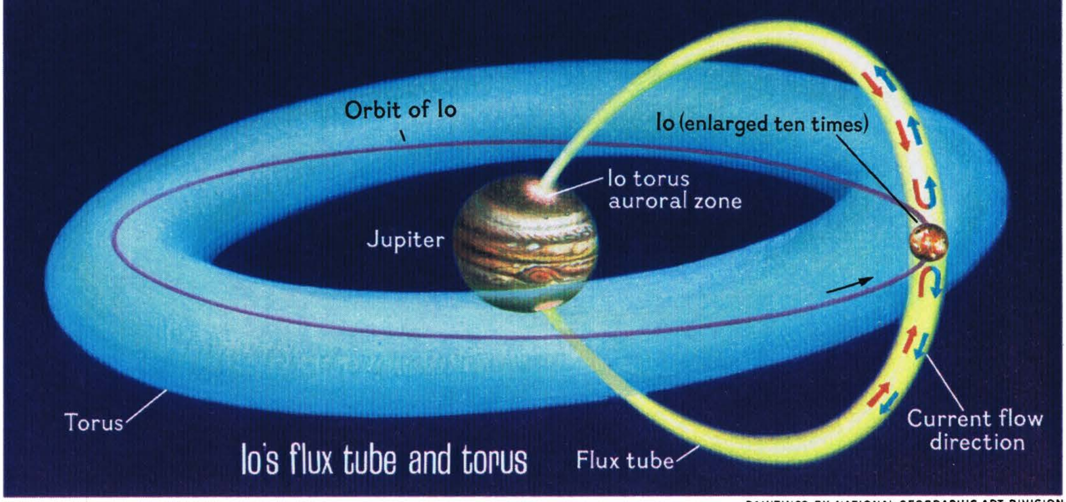


could hold two earths like peas in a pod.

The large oval to the south is also a high-pressure cell, but with different trace chemicals and only forty years old.

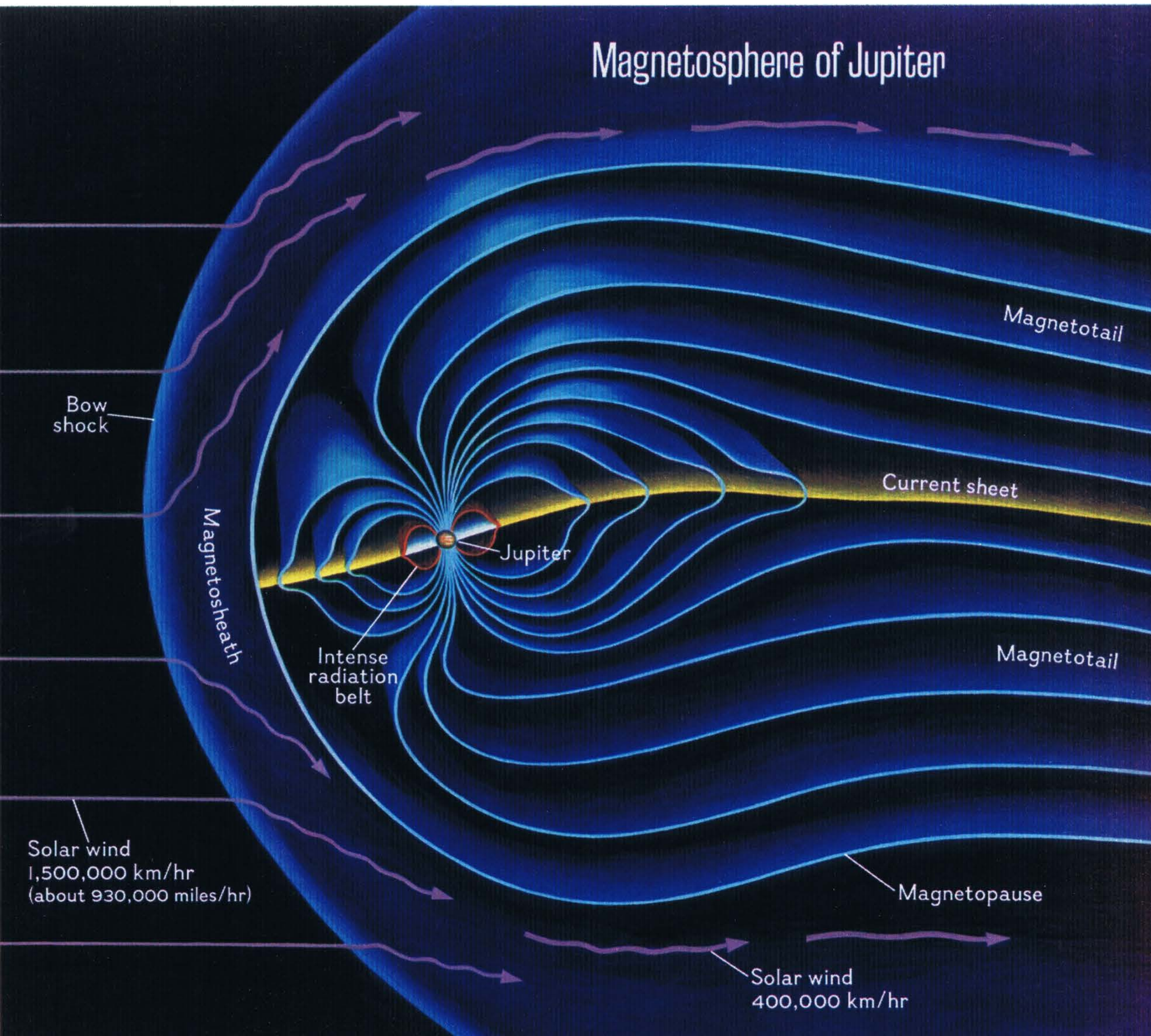
Jupiter's visible features remain intact for so long partly because, unlike earth's storms, they do not pass over varied terrain. Also, because the atmosphere is very cold and the storms large, energy tends to be lost slowly.





PAINTINGS BY NATIONAL GEOGRAPHIC ART DIVISION

*BETWEEN SUPERCHARGED Jupiter and agitated Io courses a current of five million amperes (**above,** indicated by arrows) passing in and out of a region called the flux tube. Material that escapes from Io's turbulent surface, such as volcanic gases, forms an invisible doughnut-shaped cloud, or torus, of charged particles. Voyager observed another energetic interaction—the ionized atoms of the solar wind hitting and being deflected by Jupiter's great magnetic field (**below,** cutaway view).*



(Continued from page 5) morning the stunned scientists had found not one, but at least half a dozen erupting volcanoes. Frigid on the outside, Io apparently throbs with volcanism.

Io is caught in a tug of war between Jupiter and its sister satellites, Europa and Ganymede. These tugs create enormous, pulsating tidal bulges in Io's shape. In some places Io's surface literally goes up and down a hundred meters every day and a half. It probably is these endless tugs that heat Io's crust, much as a paper clip grows hot if it is repeatedly flexed.

THE DISCOVERY of Io's volcanoes on March 9 topped off a heady week. Voyager 1 had been launched on September 5, 1977. It began taking its first pictures of Jupiter in December 1978. In mid-January at a planetary conference, imaging-team leader Brad Smith had told me calmly that a few surprises were beginning to show up in Voyager 1's first, distant images of Jupiter. The planet's cloud cover had changed considerably, he said, since two Pioneer spacecraft had flown by in 1973 and 1974 with less sophisticated cameras. Those Pioneer images had fortified the conventional idea that Jupiter's atmosphere was well ordered, with smooth, planet-encircling bands of clouds that are easily seen through telescopes on earth.


Amalthea, a small inner satellite

The closer Voyager 1 got, however, the less order it saw. Countless swirls and eddies wove through tumultuous jet streams that roar around the huge planet (pages 6-7). Near the equator one stream raced as fast as 500 kilometers an hour. Only a few degrees of latitude away another jet stream tore around the planet going in the opposite direction at 180 kilometers an hour, creating spectacular shear features. The whole atmosphere seethed like a kettle of bubbling bright paints that would not mix.

When I saw Smith again, during the encounter at JPL, he had lost his earlier aplomb. "All our theories on the Jovian atmosphere have been shot to hell," he said at a press conference. "We are like students going into an exam thinking we know all the answers and then going blank. We just don't know what to make of it."

Next came the encounters with Jupiter's moons—Io, Europa, Ganymede, Callisto.

These four moons that Galileo found in 1610 were, in fact, the first bodies in the solar system to be discovered by telescope. They range in size from slightly smaller than our moon to a little larger than the planet Mercury. Astronomers knew their sizes, densities, and overall colors. They could look at the spectra of the light the moons reflected and speculate about the materials on their surfaces. But they could say almost nothing about the geologic forces that shaped them. They were unknown worlds.

Voyager also photographed the tiny, close-in moon Amalthea, rarely seen from earth. People had imagined that Amalthea could be anything from an asteroid captured by Jupiter's great gravity to an abandoned spaceship. Voyager 1 proved Amalthea to be a dark red, rocky, cigar-shaped body.

Meanwhile, Voyager's other data continued to pour in. By week's end the 815-kilogram (1,797-pound) spacecraft had also:

• Found the Jovian atmosphere to be crackling continually with lightning. Many scientists are now convinced that this lightning must be triggering the formation of organic molecules, the chemical foundations of life, in the caldron of Jupiter's clouds.
• Discovered grand-scale auroras around Jupiter's poles.
• Seen charged particles that are much hotter than the interior of the sun.
• Found a thin ring around Jupiter. Four months later Voyager 2 took pictures of this ring, backlighted by the sun and glowing brilliantly. Analyzing the pictures, scientists were excited to discover a small, potato-shaped satellite, Jupiter's 14th known moon, on the ring's outer edge. These discoveries make rings a major new realm of planetary inquiry. Where do ring particles come from? In Jupiter's case they could flow in from Io's volcanoes. Perhaps they are debris from comets or the ejecta from meteorite impacts on the inner moons. Jupiter's new moon actually may be

what defines the edge of the ring, sweeping up the particles at the ring's outer limits.

Astronomers used to ask why only Saturn has rings. Recently Uranus was also found to be ringed. Now suddenly the question is: How many rings are there? And do they all, including Saturn's, have little moons?

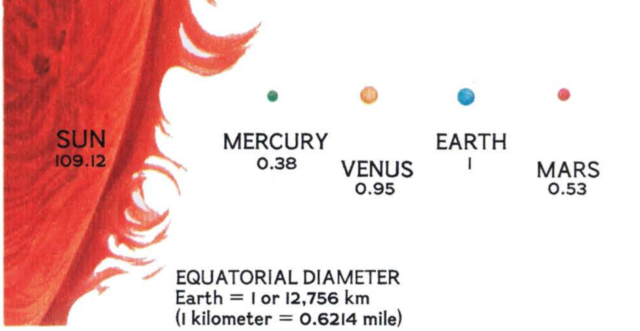
JUPITER, the Roman mythological king of the heavens, is a fitting name for the planet visited by Voyager. When the solar system was born some 4.6 billion years ago, Jupiter swept up more than 70 percent of the material available to the planets. It probably formed swiftly from a swirling disk of dust and gas millions of kilometers wide. At its most dramatic stage, this disk collapsed—possibly in just three months—into a glowing red ball some 200,000 kilometers wide. It has now shrunk to 143,000 kilometers. It orbits 778 million kilometers from the sun.

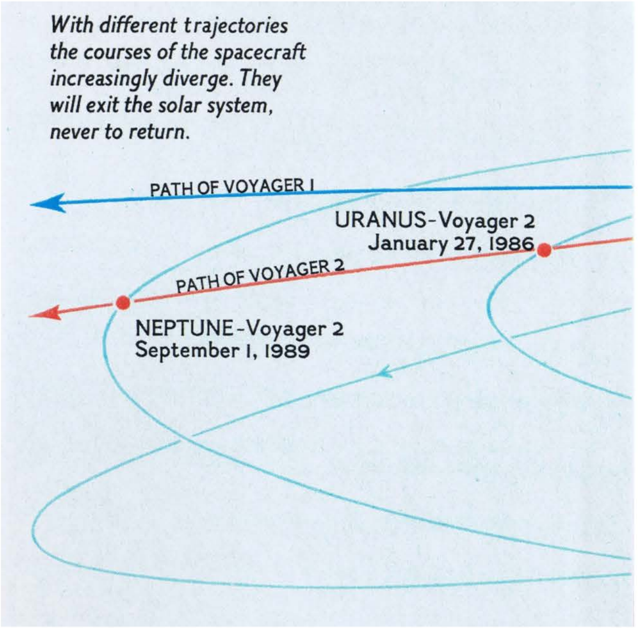
Some 1,300 earths could fit within Jupiter's volume. Jupiter has 318 times the mass of earth, yet only one-fourth its density. You might think of Jupiter as a great gasbag. If you could put it in water, it would almost float. This balloon rotates so rapidly that its day takes only ten earth hours, but its year, because of Jupiter's longer path around the sun, lasts 12 earth years.

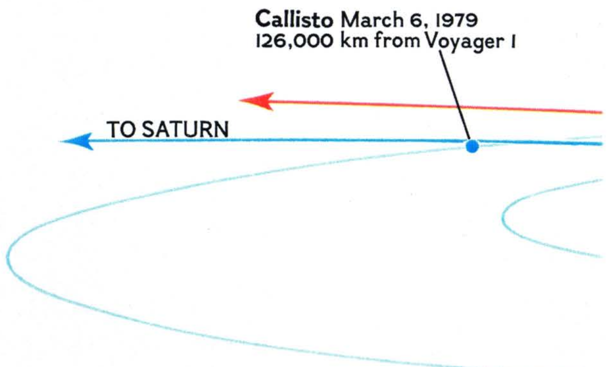
All anyone can see of Jupiter are its clouds, which go down only a hundred kilometers. Deep within, the planet probably has a molten core of silicates and metals the size of the earth. Otherwise its composition is much like the sun's—massive quantities of hydrogen and helium. These gases mix and probably form shells tens of thousands of kilometers thick around the core.

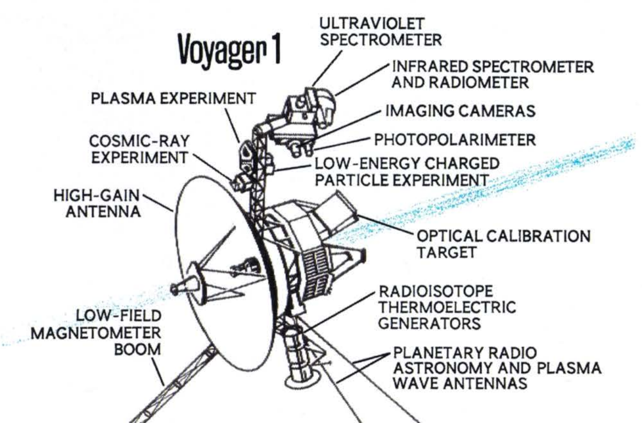
When Jupiter originally collapsed, tremendous heat was unleashed. Some of that intense heat of formation was trapped within the planet and is still slowly leaking out. Although temperatures at Jupiter's cloud tops are colder than minus 120°C (minus 184°F), its center may reach 30,000°C (54,000°F), or five times that at the sun's surface. The pressure near the center equals a hundred million earth atmospheres.

Under these conditions hydrogen liquefies and also becomes metallic. This metallic form is an electrical conductor, and as the great internal *(Continued on page 16)*

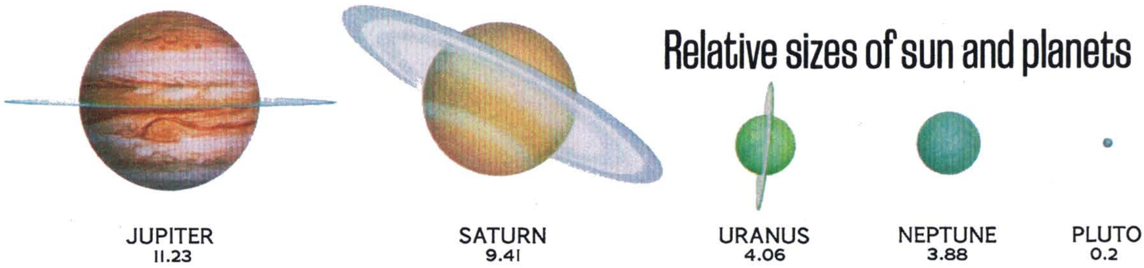




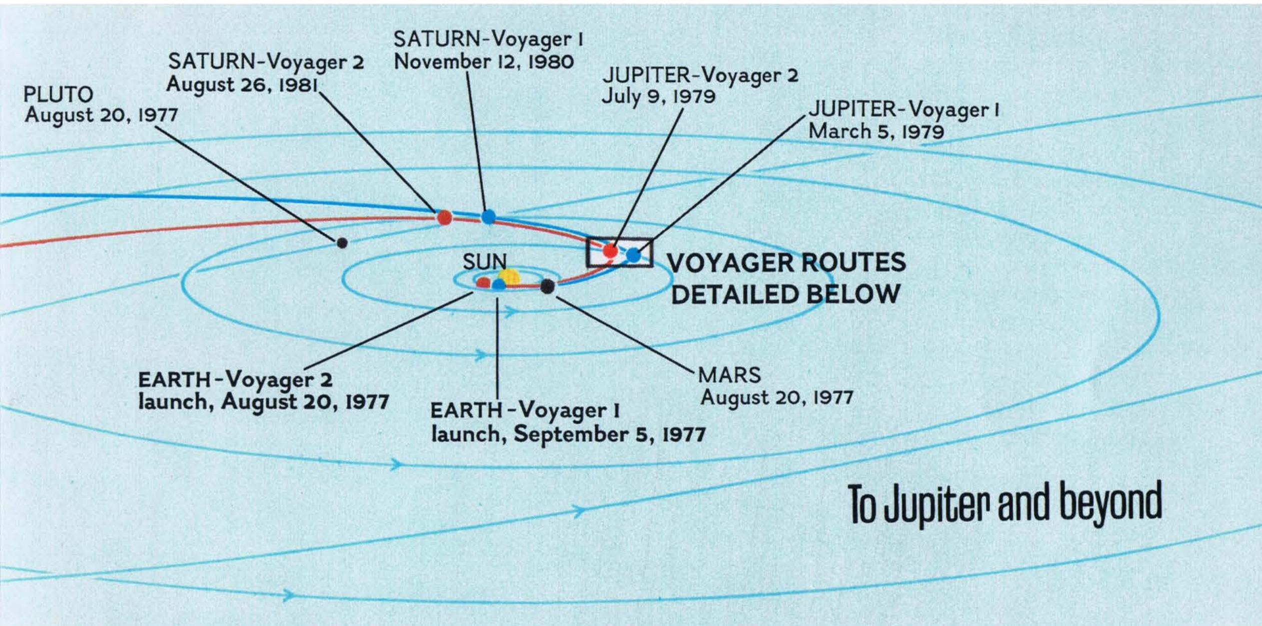




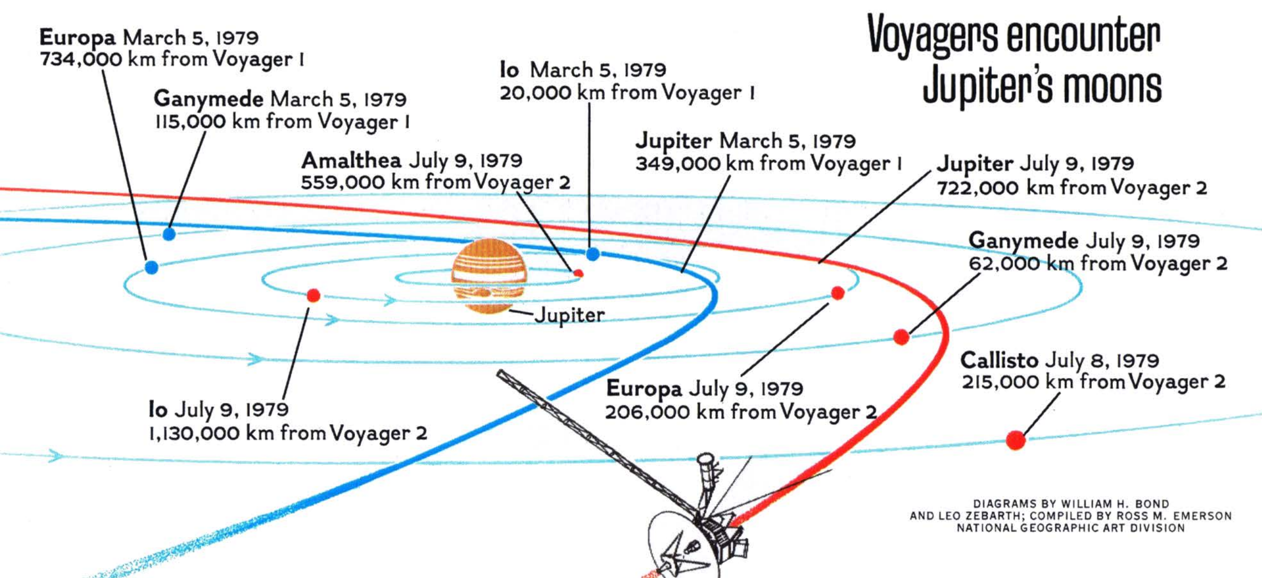
Relative sizes of sun and planets



To Jupiter and beyond

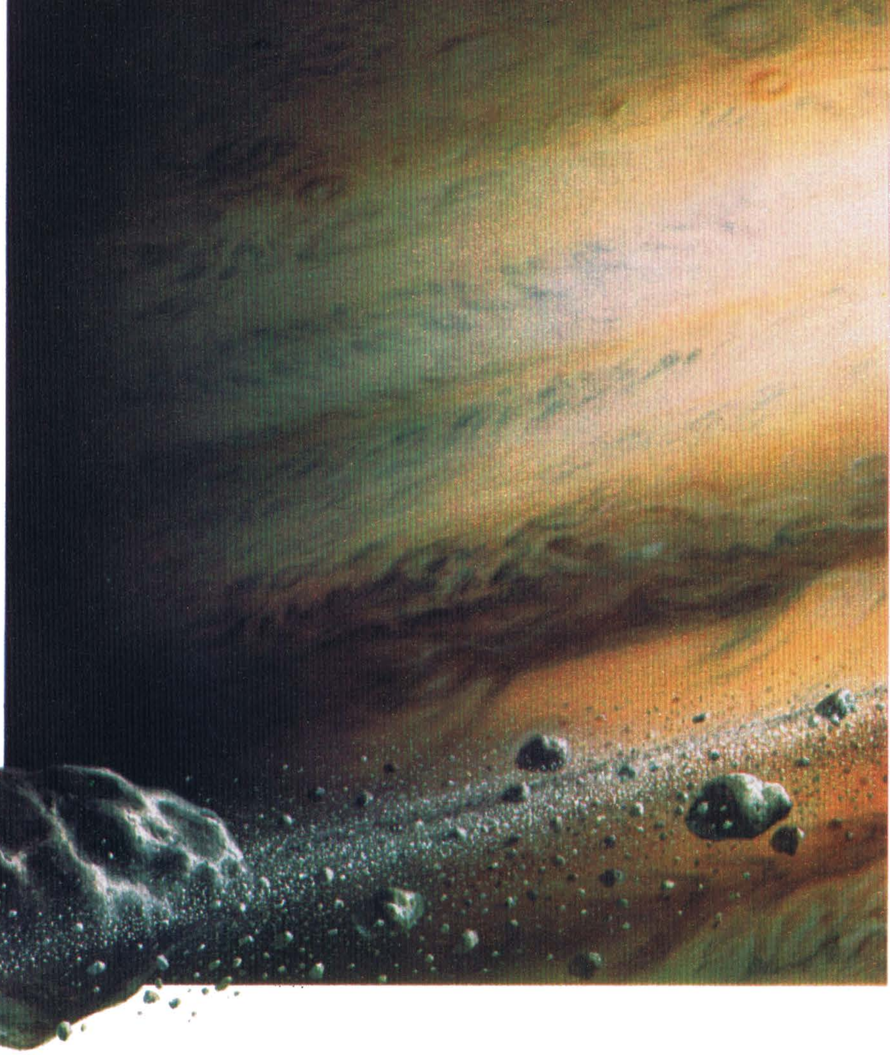


Voyagers encounter Jupiter's moons

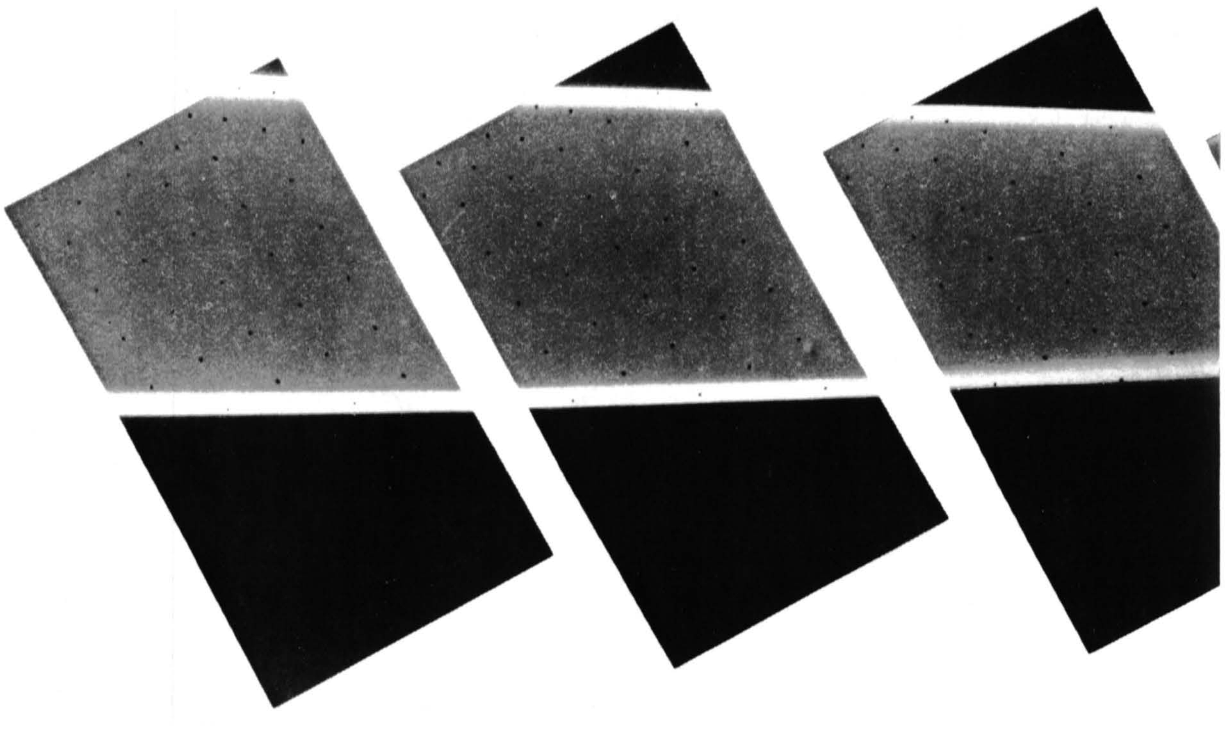


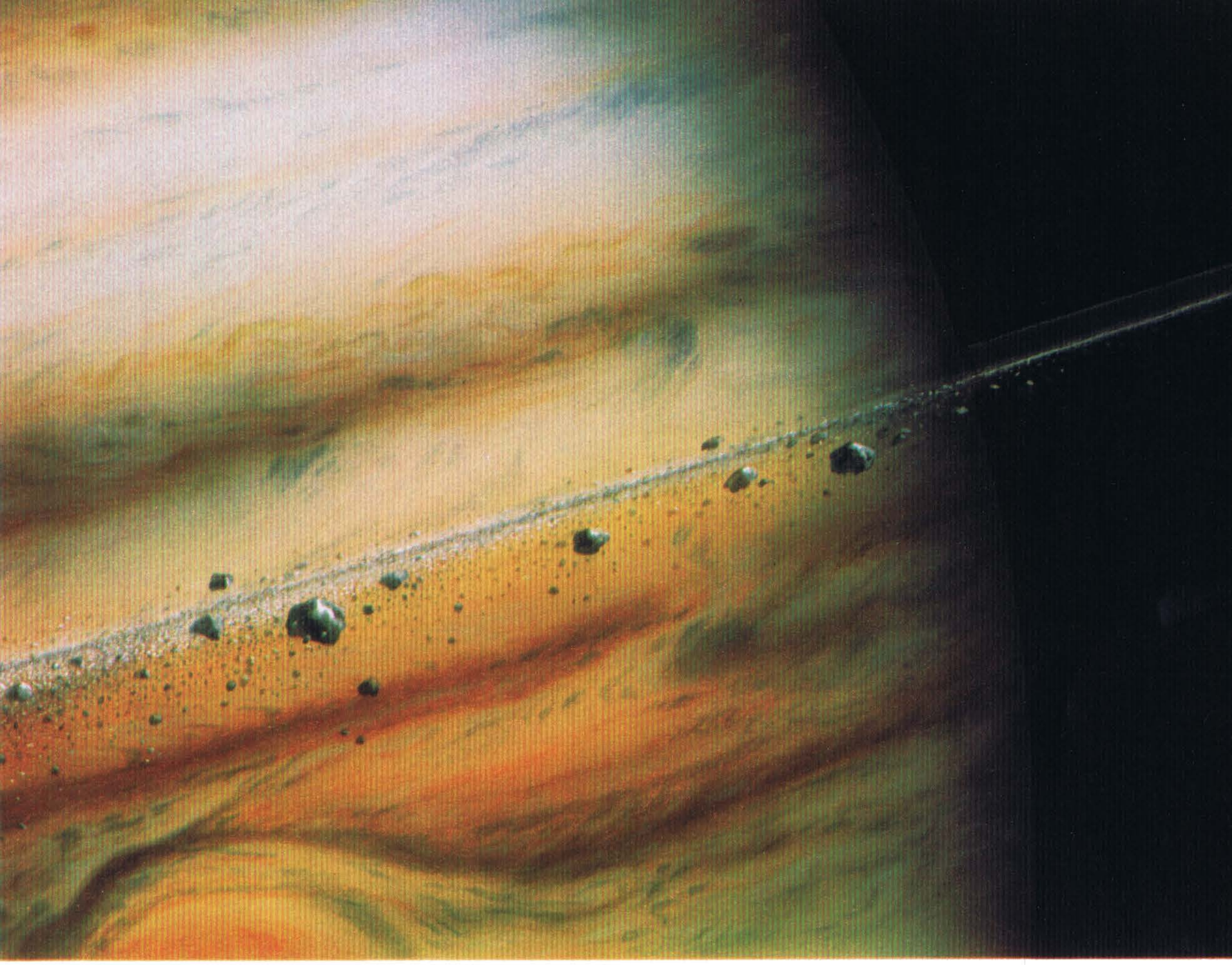
DIAGRAMS BY WILLIAM H. BOND AND LEO ZEBARTH; COMPILED BY ROSS M. EMERSON NATIONAL GEOGRAPHIC ART DIVISION

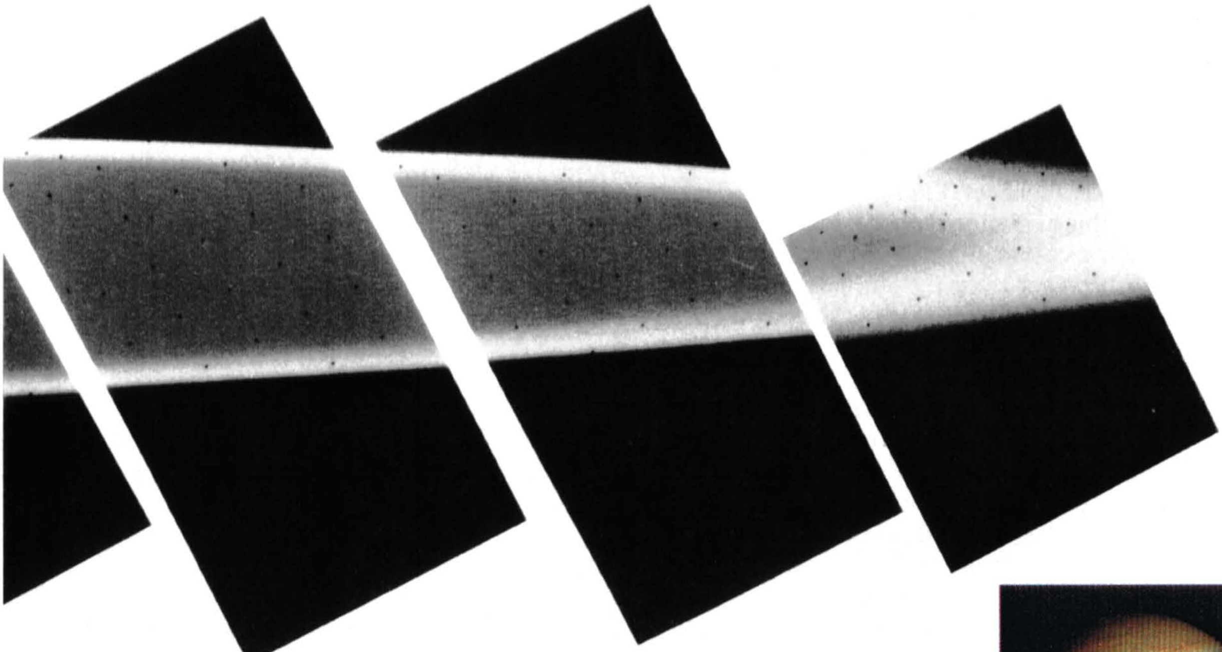
IDENTICAL CRAFT weighing less than a ton each, but packed with sensitive instruments, Voyagers 1 and 2 were launched 16 days apart in 1977. On a faster trajectory, Voyager 1 leads the way. Voyager 2 backs it up and is targeted to further explore findings of Voyager 1 or investigate areas it could not. Both will go on to Saturn, and, if all goes well, Voyager 2 will fly by Uranus and Neptune before sailing out among the stars.



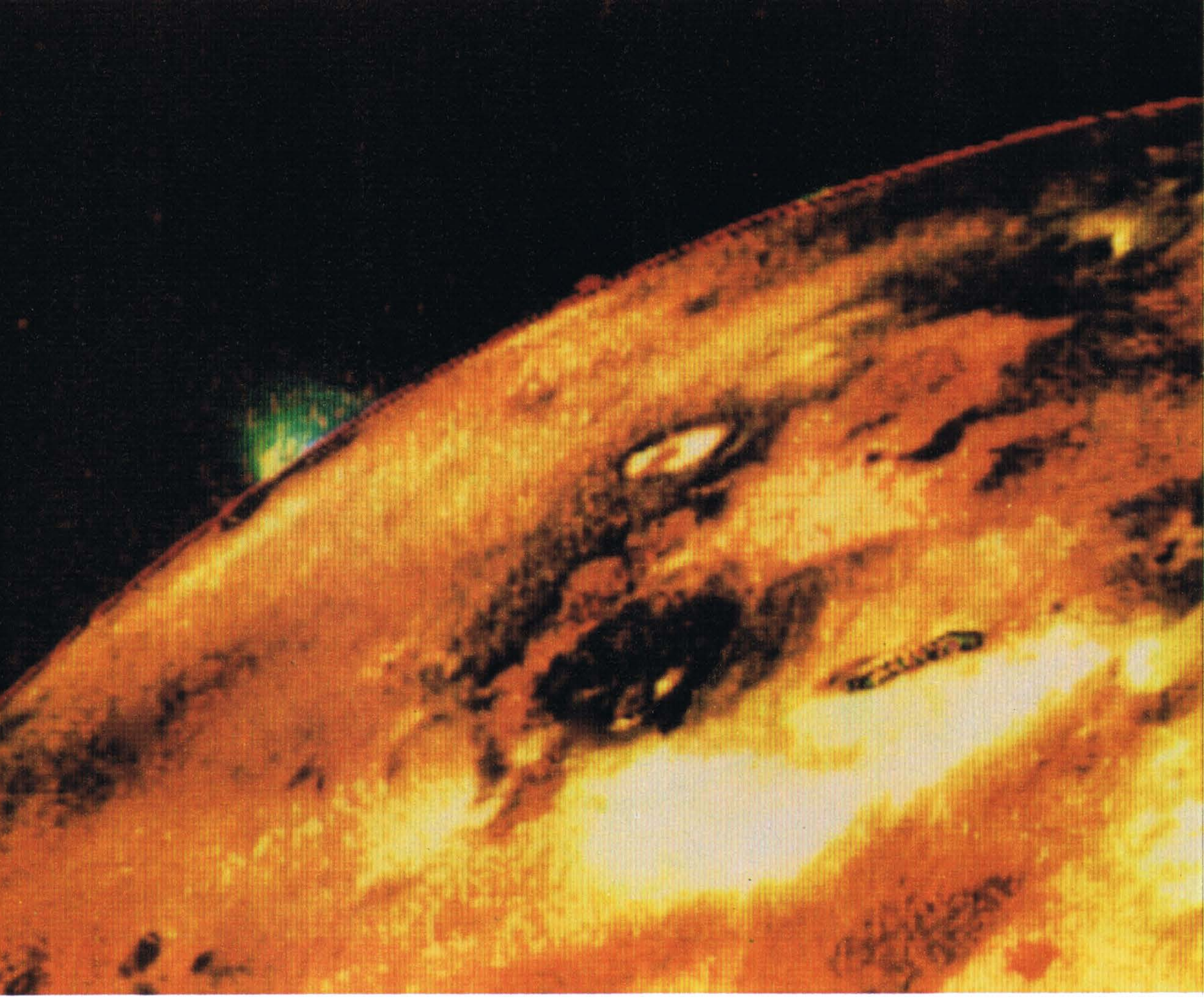
A GREAT SURPRISE sent by Voyager 1 was the faint image of a ring extending 58,000 kilometers (36,000 miles) from Jupiter's cloud tops, perhaps debris from Io's volcanoes. Artist Ludek Pesek paints it as composed of rocky material **(right)***. Voyager 2 images* **(below)** *suggested that most of its particles are too small to be seen with the naked eye. They are visible only as a mass when sunlight strikes them from behind, much as dust motes floating in a room are seen in a shaft of light. (Black dots are part of the imaging process.) But later study showed a tiny rocky satellite, Jupiter's 14th known moon, at the edge of the ring.*







What Voyager Saw: Jupiter's Dazzling Realm



heat stirs the liquid up, it creates a huge magnetic field around Jupiter. The field extends out around the planet as far as seven million kilometers, entrapping trillions upon trillions of high-energy particles in invisible radiation belts.

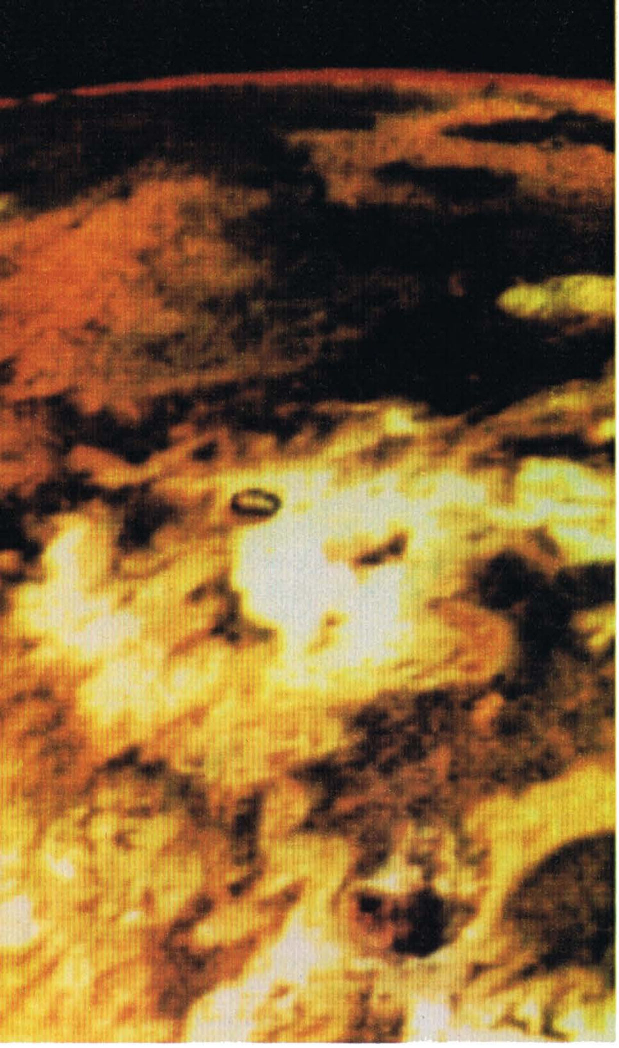
This vast region, the magnetosphere, is much bigger than the sun (lower diagram, page 10). It is four times as far away from us as the sun, but were it visible, it would appear larger than our moon.

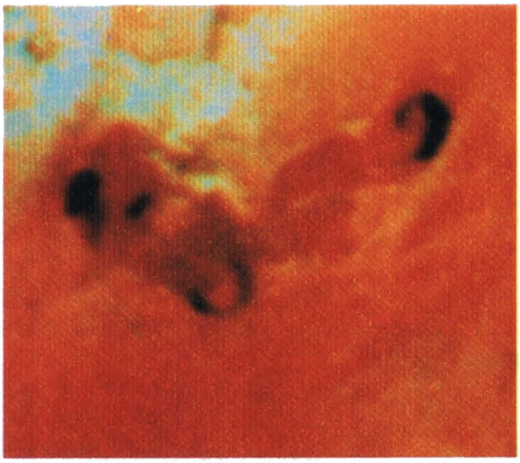
Sometimes the magnetic field releases bursts of its trapped particles. These cosmic rays have been detected as far away as Mercury, some 700 million kilometers. Until the 1940s it was believed that most cosmic rays came from outside the solar system. Today we believe many are spun off from Jupiter.

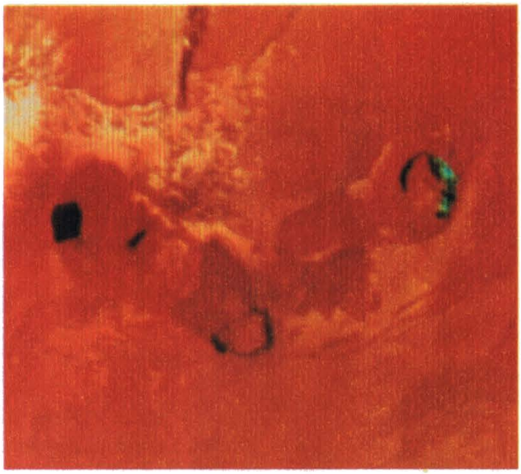
All the Galilean satellites are embedded within Jupiter's magnetosphere. They are bombarded by high-energy electrons, protons, and other ions so lethal that man could not hope to land on any Galilean moon, except perhaps Callisto, the farthest out. This radiation is actually eroding Io's surface atom by atom. These surface particles, along with those from Io's volcanoes, are captured by Jupiter's magnetic field and create a charged gas cloud, called a torus, that Io moves through as it orbits.

Furthermore, as Jupiter's magnetic field sweeps past Io, it generates an electric current flowing between the planet and its moon (upper diagram, page 10). Voyager 1 measured the current at five million amperes. This translates into two trillion watts, or the capacity of all earth's power plants. Some scientists speculate this power may help heat Io to its hyperactive state.

LAST FEBRUARY 28, Voyager 1 hit the leading edge of Jupiter's great magnetosphere. The encounter was under way. Scientists call this leading edge the







bow shock. It is indeed an area of great shock, for it is there that the forces of the sun clash with those of Jupiter.

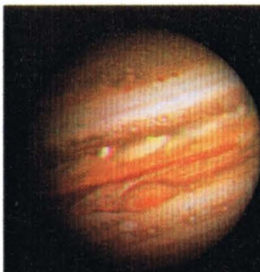
The sun's outer surface is continuously blowing away, sending out streams of hot ionized gases called the solar wind, which is traveling at a million and a half kilometers an hour when it collides with the bow shock. Then its speed suddenly slows to only 400,000 kilometers per hour—and most of its particles are deflected.

Prior to Voyager, it was thought that some particles would leak through the tail end of this shield and be carried right into Jupiter's polar regions. There they would strike atoms in the atmosphere, which in turn would glow, creating auroral displays like those on earth. Voyager did indeed find great auroras, but their cause was a surprise. Those auroras, at least, are apparently triggered not by solar-wind particles, but by electrons streaming in from Io's torus.

*PULLED AND TUGGED by the gravity of Jupiter, Europa, and Ganymede, the crust of Io seethes with tidal forces that heat its upper layer, inducing volcanism. Eruptions spew a hundred kilometers or more above the surface (**left**), unchecked by atmosphere or strong gravity.*

*Voyager 1 also recorded splotched terrain (**top**), marked by black spots and crescents. Six hours later, bluish clouds, probably of sulfur dioxide (**above**), had appeared over the crescent at right.*

Were Io an earth satellite, it would shine six times brighter than our moon.

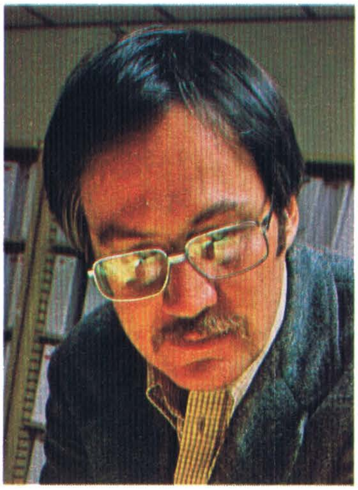


Three views of eruptive Io

HAROLD MASURSKY

What causes Io's volcanism? Based on Voyager observations, scientists have constructed various models to explain it. Harold Masursky of the U. S. Geological Survey postulates a mechanism in which sulfur-enriched silicate magma erupts through a silicate crust rich in sulfur—a process similar to earthly volcanism but richer in sulfur. Variations in the chemistry of the magma chambers and in their physics account for different types of eruptions and, therefore, different features on Io. In this model, surface sulfur is shown as a light coating.

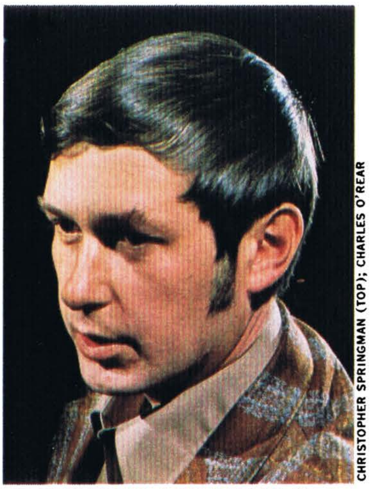
Masursky does not feel that the Voyagers' "eye-blink" view of Io can be projected across its entire history. "The bodies that we know best—earth, the moon, and Mars—have had highly variable periods of activity." Why, he argues, should Io be the lone exception? But: "No geologist trained to approach complex geologic phenomena would propose one model as solving the problem."



BRADFORD A. SMITH

"Whatever sulfur can come out of Io's interior has come out," asserts imaging-team leader Bradford A. Smith of the University of Arizona. He cites the billions of years of tidal heating, a much more energetic and constant process than the breakdown of radioactive isotopes that heated earth's core. In his model sulfur four kilometers deep has been forced above the silicate subcrust, and when silicate volcanism occurs, it is under a sulfurous crust and a liquid sulfur ocean. This, Smith thinks, has been going on for four billion years and is a self-limiting system: "If you were to dump more sulfur on the surface of Io, an equal amount would seep back into the molten silicate interior." Violent volcanism occurs in the crust when liquid sulfur dioxide (SO_2) meets molten sulfur, producing explosive decompression of the SO_2.

A choice between the two models—or others—may have to wait upon Galileo, a spacecraft scheduled for the mid-1980s.



CHRISTOPHER SPRINGMAN (TOP); CHARLES O'REAR

LAURENCE A. SODERBLOM

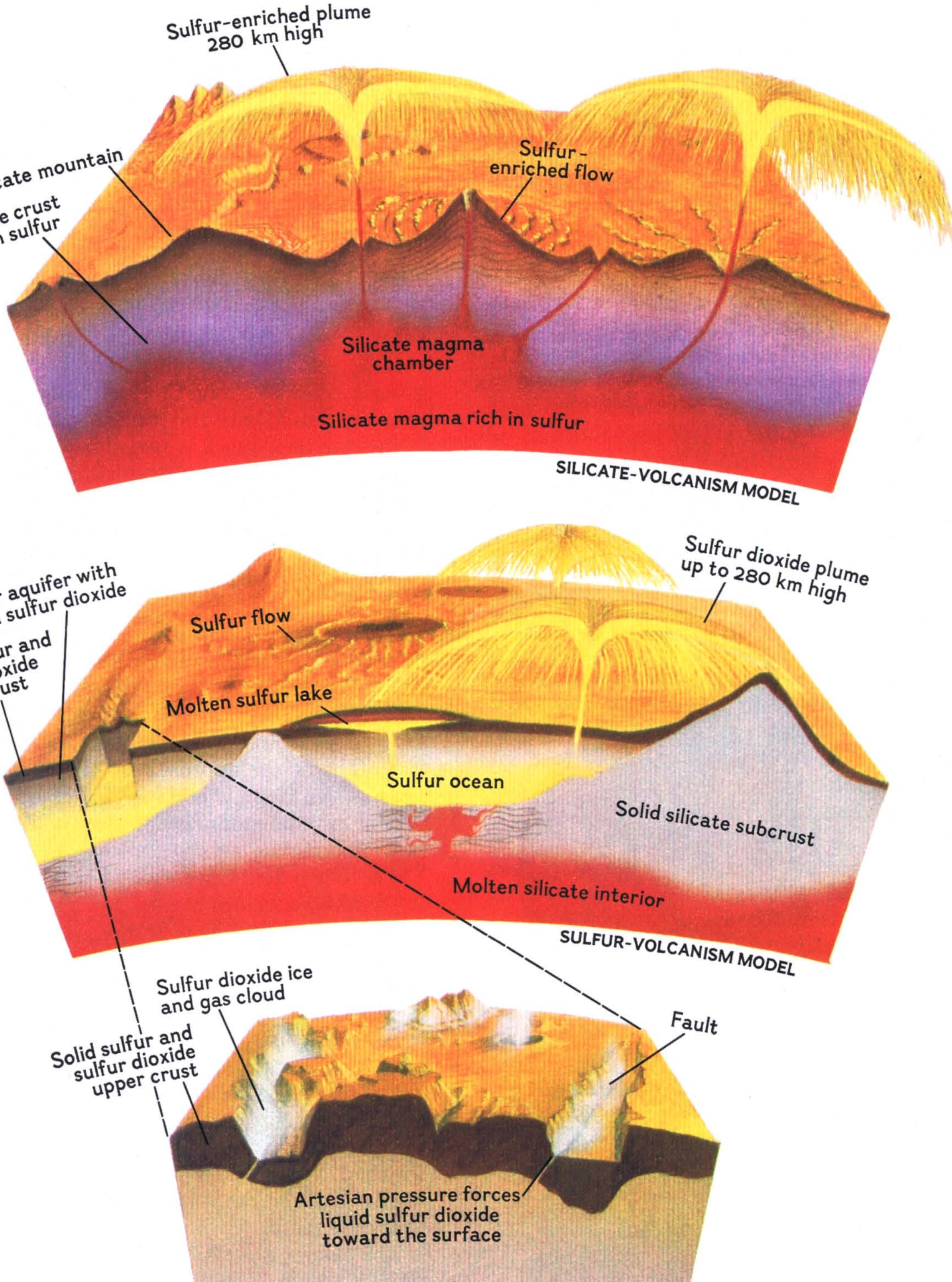
A different kind of eruption was seen mainly in the south polar region where terrain resembles parts of the American West, with eroded cliffs and isolated mesas.

According to the U. S. Geological Survey's Laurence A. Soderblom, gas-ice mixtures of SO_2 blast away from the base of the cliffs like ten thousand Old Faithfuls.

Liquid SO_2 percolates up or is forced up from the aquifer by artesian pressure. When it has risen near the surface, the SO_2 can no longer remain stable as a liquid. It explodes into a gas and ice cloud like a carbon dioxide fire extinguisher going into action.

Pressures are great enough to erode the cliffs and to send the SO_2 spewing out as far as fifty kilometers, where it falls as snow, collecting in the fashion of the Antarctic ice cap.

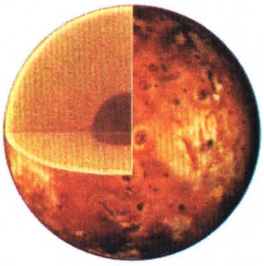
"I suspect," Soderblom says, "that those cliffs are actually slabs of solid SO_2."



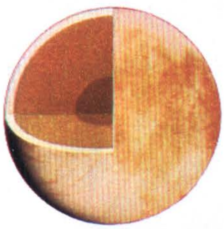
PAINTED BY JAIME QUINTERO
NATIONAL GEOGRAPHIC ART DIVISION

Galilean moons vary in makeup and size

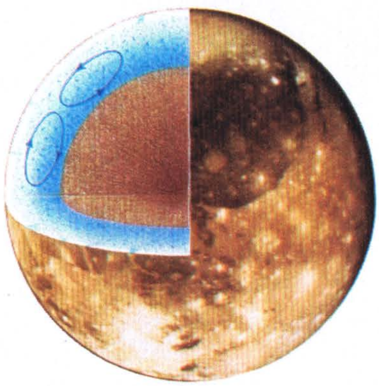
INTERIOR MODELS PROVIDED BY TORRENCE V. JOHNSON, JET PROPULSION LABORATORY



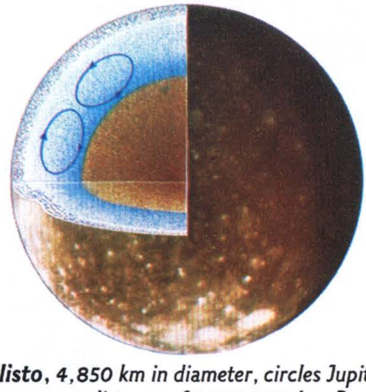
***Io**, 3,640 km in diameter, circles Jupiter at an average distance of 421,600 km. Probable structure: sulfur and sulfur dioxide crust, molten silicate interior, and possible solid core.*



***Europa**, 3,130 km in diameter, circles Jupiter at an average distance of 670,900 km. Probable structure: ice crust, silicate interior, and possible solid core.*



***Ganymede**, 5,270 km in diameter, circles Jupiter at an average distance of 1,070,000 km. Probable structure: ice crust, convecting water or soft ice mantle surrounding silicate core.*



***Callisto**, 4,850 km in diameter, circles Jupiter at an average distance of 1,880,000 km. Probable structure: thick ice crust, convecting water or soft ice mantle surrounding silicate core.*

Voyager also found charged particles of sulfur from Io as far out as the bow shock. Some of these particles had been heated, perhaps by their interactions with the solar wind, to more than 300 million°C, the highest temperature known in the solar system. However, so few of these particles exist in the magnetosphere's near vacuum that their intense heat had no effect on the spacecraft. Nor would they on a human being.

The bow shock is in constant motion. If the solar wind is blowing hard, the bow shock may be pushed in as close to Jupiter's surface as four million kilometers. Voyager 1 met the bow shock five times as the magnetosphere pulsed back and forth in space.

But the bow shock is invisible, and for drama it could not compete with the pictures Voyager was sending back.

As Voyager closed in, its cameras could no longer take in the whole globe. I think all of us at JPL began to tingle. We almost felt we were on board the spacecraft, doing a slow and relentless zoom into a secret corner of the universe that was intricate and bizarre beyond our fantasies. A picture would flash onto the screen. "Oh, no! This can't be real," I would say to myself. "This is over the rainbow. This is the approach to heaven—at least as Van Gogh would have painted it."

Soon a more stunning image would appear, making the last one seem obsolete.

The Great Red Spot swirled before us. For a time we seemed headed down into the center of this mysterious vortex, which has been observed for at least a century and is easily big enough to swallow two earths.

We saw three whirling white ovals below the red spot. Astronomers had puzzled over these ovals in particular, because their birth had actually been observed forty years ago out of a thin white cloud streaming around the planet. In time-lapse films scientists watched what looked like thunderstorms raging in plumes that rose from the clouds near the equator.

The moons, too, rapidly grew larger. Until now they had seemed to be more myth than real other worlds.

All the Galilean satellites had been named after objects of the mythological Jupiter's wide-ranging fancies. Callisto, the most distant satellite, is the namesake of a beautiful maiden who enticed Jupiter and thereby provoked the jealousy of his wife, Juno. Juno destroyed Callisto's allure by turning her into a bear. A similar fate befell Io, the inspiration for the closest Galilean moon. After her romance with Jupiter, she ended up as a heifer, pursued by Juno's gadfly.

The two middle moons inherited their names from more fortunate friends of Jove. To elude the watchful Juno, he approached beautiful Europa as a bull. His noble gentleness seduced Europa. She climbed upon his back, and the two flew off to Crete, where she became an object of worship. Ganymede, a handsome youth, also caught Jupiter's eye, and he whisked the boy away to become the cupbearer to the gods.

THE FIRST ENCOUNTER was a distant, glancing look at Europa, as Voyager 1's trajectory sped it in for its swing around Jupiter. Unfortunately, from more than a million kilometers out the craft saw only enough of Europa to tantalize.

"It looks like the earth in a deep ice age with all its oceans frozen," said imaging team member Larry Soderblom.

Enormous and mysterious stripes crisscrossed Europa, raising questions only Voyager 2's much closer flyby four months later could clarify.

For the time being, everyone's attention was easily distracted by Io. White patches on its surface radiated brilliantly amid mottled shades of red and orange. When he saw one of the first close-ups, team leader Brad Smith said that Io looked like a pizza.

A heart-shaped region a thousand kilometers across, which in a few days proved to be the deposits laid down by an active volcano, dominated early Io images. Then, as the spacecraft drew close, it found strange black hot spots—later speculated to be crusted-over lakes of lavalike sulfur. Here and there rose mountains as high as ten kilometers—perhaps remnants of an earlier crust.

Disturbingly, Voyager 1 did not see a single meteorite crater on Io. On earth such processes as weathering and volcanism have erased most craters. But the surfaces of every solid body we have studied in the solar system—the moon, Mercury, Mars and its moons—are peppered with them. Crater counting has become a cornerstone of planetary sciences, the way that scientists date features on other planets. Basically, the more craters a surface has, the older it is.

"We were terribly upset to see no impact craters on Io," recalled Smith. "If our theories were right, the absence of craters meant that some processes had to have reworked Io's surface within the past million years. That's just a blink of an eye geologically."

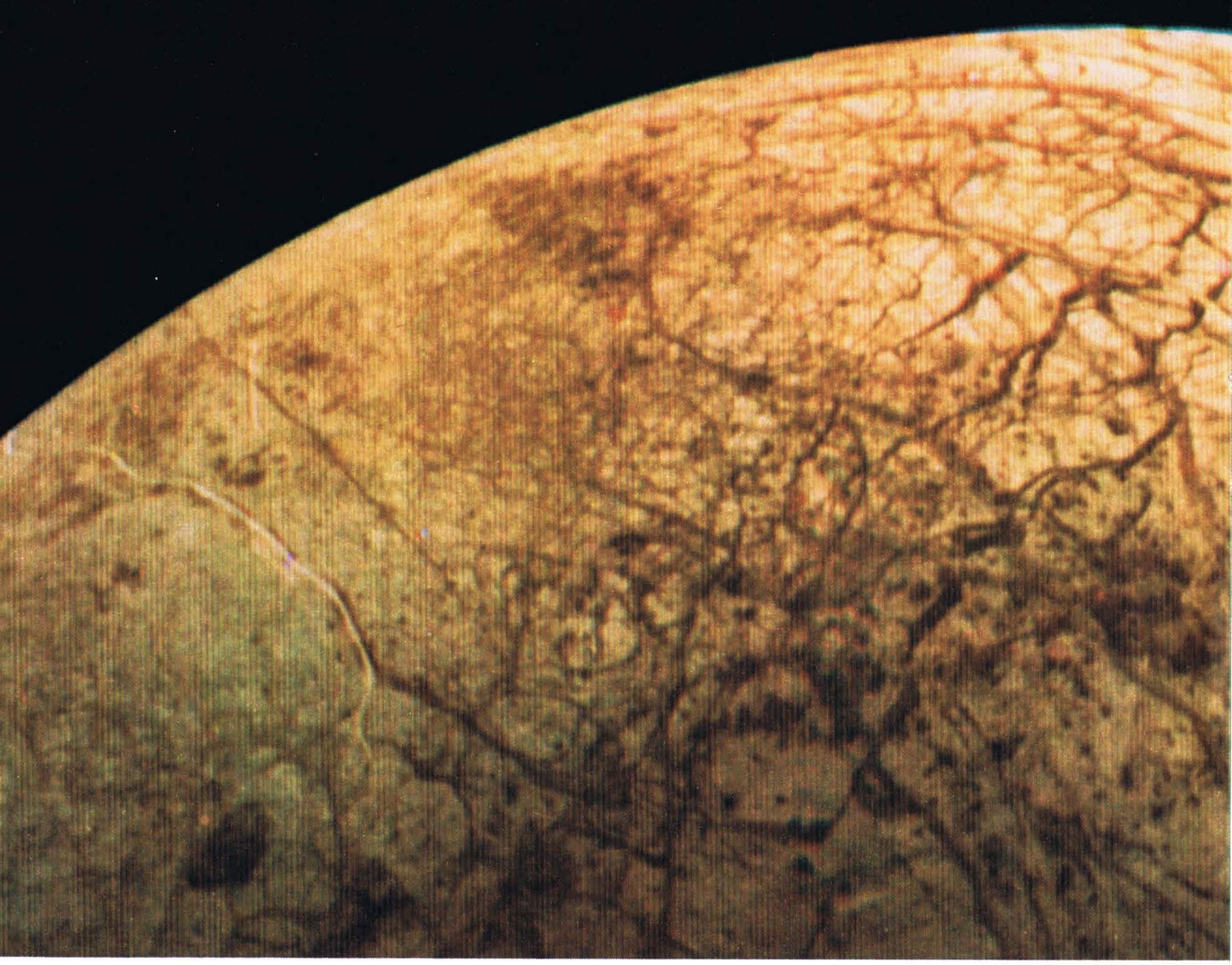
The team anxiously awaited close-ups of the next moon, Ganymede. If Ganymede also lacked craters, then the idea that meteorites bombarded the entire solar system would be suspect. Or perhaps Jupiter had somehow protected its moons from the meteorites that struck the inner planets. In either case a vital method of dating bodies in the solar system would be lost.

The weary team sequestered themselves in their conference room to greet the first Ganymede close-ups. It took only a few seconds for Larry Soderblom to cry "Crater!" His colleagues cheered with relief. They quickly found several more, and champagne corks blew.

Ganymede had more than craters to display. Its crust appeared broken into fragments, like the pieces of a mosaic. These pieces seemed to be made of two distinct types of terrain. One had shoulder-to-shoulder craters; the other looked heavily grooved, as if someone had raked it.

There was scarcely time to puzzle over these features, however, before Callisto close-ups began coming in. Mercury-size Callisto was darker, but its surface was pricked by innumerable bright craters.

Callisto apparently had been severely battered during its youth. One giant impact region has concentric ridges that look like frozen ripples and extend for 3,000 kilometers. This was surely one of the most cataclysmic meteorite strikes to ever occur in the solar system. The crater counters quickly realized that all of Callisto and much of Ganymede are completely saturated with craters. That means their surfaces are extremely old. These moons, we can safely say, have been dead a long time. However, Io's surface, as the discovery of volcanoes would reveal, is being reworked continuously.



Europa

Cue ball of the satellites, Europa may prove to be the smoothest body in the solar system. Streaks that paint its surface were probably fissures in the surface ice

BY THE TIME Voyager 2 flew by in July, the scientists had digested their data better, but the excitement over Io had scarcely diminished. Linda Morabito had discovered her volcano, and the surface of Io was confirmed to be the youngest known in the solar system.

One of the first things the scientists noticed in the new Io pictures was that the huge heart-shaped volcanic region they saw earlier had changed into an oval. The volcano's debris pattern had inexplicably shifted, and the volcano itself had shut off. However, six other volcanoes were still erupting and presumably had been doing so continuously since March.

Callisto looked as dead as it had on the first flyby, but Ganymede's terrain, seen closer up, appeared much more complicated. There were a smooth and relatively young basin, an adjacent mountainous region, and remnants of a great ancient meteorite crater like the one on Callisto. Apparently early in its youth Ganymede had a convulsive period that lasted long enough—perhaps several hundred million years—to rework part of its surface.

Europa, however, was Voyager 2's star. The scientists were predicting that water-rich Europa could be heated by the same kind of tidal tugging as Io—albeit much less so. "We were hoping to see Old Faithful going off," said geologist Hal Masursky.

Voyager 2 saw no geysers—but its resolution was only good enough to detect mammoth ones. The great global stripes that Voyager 1 had spotted proved spectacular close up. They made Europa resemble a cracked white billiard ball. Yet the "cracks" had no relief. They looked almost painted

that were filled by upwelling water or soft ice. Their patterns suggest that at one time Europa's ice crust was expanding and cracking on a grand scale. Only a few impact craters mar the moon's surface, indicating it is relatively young.

on. All of Europa, in fact, turned out to be remarkably flat with few craters. So the scientists concluded that Europa has a relatively young surface.

An Io-like tidal heating may indeed be keeping the crust of Europa plastic and the ocean beneath its icy surface either liquid or soft ice. But no one can do more than guess at what mechanisms Europa uses to erase its craters.

DESPITE many unanswered questions, we now know enough about these four new worlds to imagine visits to them. If we landed on Io first, 421,600 kilometers from Jupiter, this is what we would probably see.

Most of Io would look like a painted desert with an intermingling of sulfurous colors (page 16). Sulfur dominates the landscape because all lighter materials, such as water, have been lost to space. In fact, Brad Smith holds that sulfur is Io's water, and that the surface of the moon has a four-kilometer-deep sulfur ocean (page 19). Only the upper kilometer or so of this sulfur sea is frozen. Below, the sea would be molten.

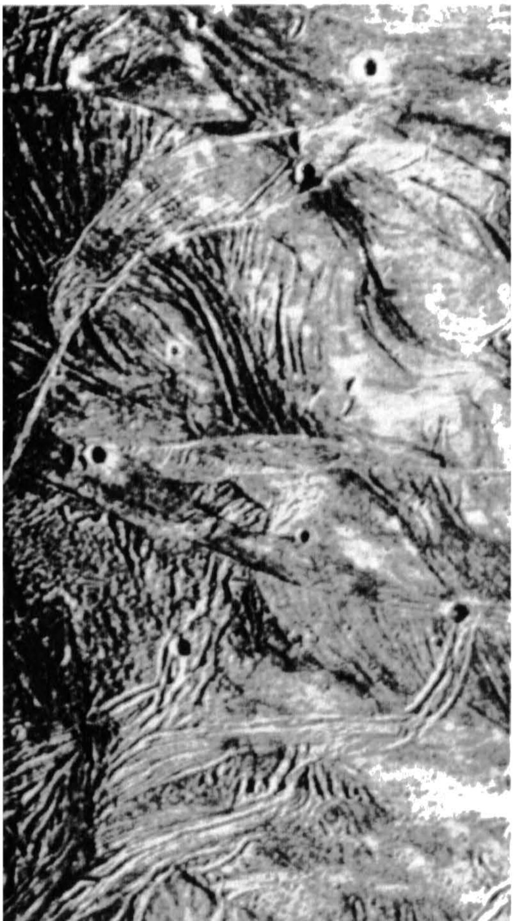
Hal Masursky, on the other hand, says that the sulfur on Io is basically a dusting that covers up a silicate landscape similar to volcanic regions found on earth. In either case, Io's volcanoes are blowing off a lot of sulfurous material. Most falls back on the surface, but about a hundred kilograms a second escape the moon.

The sulfur dioxide blown off creates a tenuous, foul-smelling atmosphere. If we were walking across Io, a

Ganymede

*Darkest is oldest: This rule applies to the icy surface of Ganymede, dirtied by debris accumulated early in its history and most visible in a large circular area (**below**). Brightest is youngest: Fresh white ice was ejected by the most recent meteorite impacts (**left**).*

*To geologists, the most intriguing features are sinuous strips of alternating parallel grooves and ridges (**bottom**) that indicate crustal movement billions of years ago.*



pastel yellow, orange, and bluish white snow might fall on us. If we visited the satellite's poles, we would find deep banks of this sulfur dioxide snow.

These polar snowbanks have big, puzzling scarps, which on earth we would say had been carved by wind or water.

But Io has no wind and is utterly arid. Most likely this erosion comes from within, when high-pressure liquid sulfur dioxide, trapped beneath the surface like water in an artesian well, manages to break through. As it does the liquid explodes into the atmosphere in a gas and ice cloud, and the ground above its former reservoir collapses.

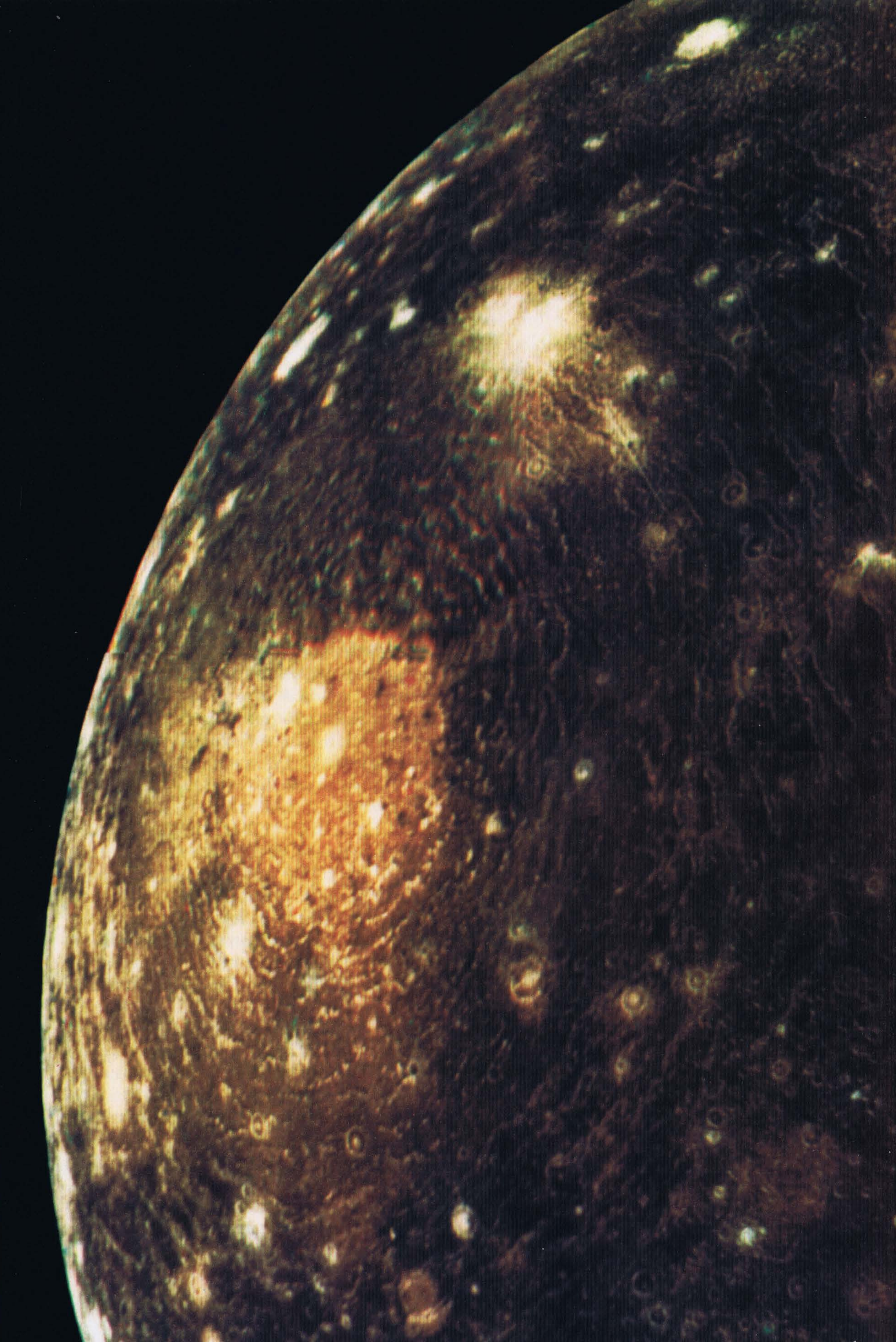
Moving toward Io's equator, we would walk across large white patches of sulfur dioxide frost, or come to the shore of one of the crusted-over black lakes. These lakes could be floods of black molten sulfur flowing out from fissures and freezing over. Or they could be created when a surge of heat from the interior melts pieces of the surface.

If we approached one of Io's large volcanoes, the moon's flatness would break suddenly. From the center of the caldera, which might be tens of kilometers wide and a kilometer deep, we would see an erupting storm throwing debris skyward at nearly one kilometer a second, comparable to the most violent eruption of Mount Etna. Like a rain of bullets, blobs of sulfur would pour down on us at the same speed.

IF WE COULD MOON HOP, we would be eager to go 250,000 kilometers farther out from Jupiter and descend on Europa, a totally different world.

We would probably land on the ice ocean that dominates the surface of Europa. It would be like landing in the Arctic Ocean and trudging across pack ice. We would find the horizon relentlessly flat. If we walked across one of the great stripes, we might know it only by the darkened color. It would be like crossing translucent garden mud in winter. We would surely pause to try to determine what had caused these stripes.

The surface would feel like crusty snow, and our feet would occasionally punch through. We might pass vast regions of smooth ice ponding,

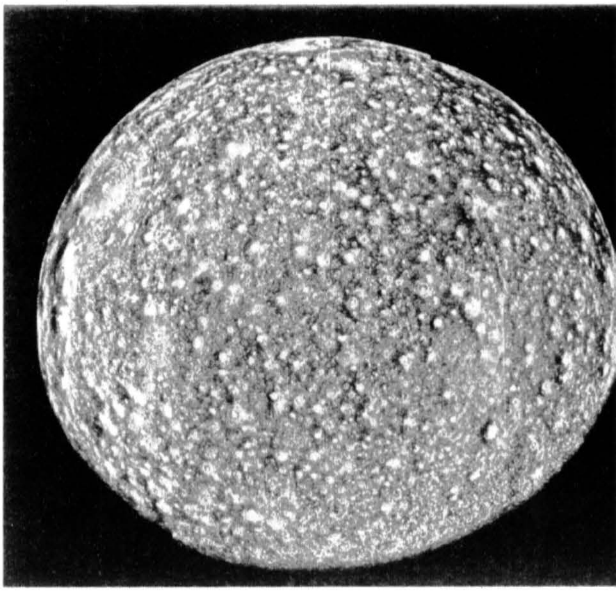


Callisto

The ghost of a huge meteorite appears as a light-colored circle surrounded by concentric ridges heaved up by its collision with Callisto ***(left)****. The impact basin has been filled in by ice, and, though later battered by smaller meteorites, is nearly level.*

Unlike Ganymede, where crustal faulting and movement reworked the surface, Callisto shows a more nearly complete record of impacts. Seen in a different view ***(right)****, they stand shoulder to shoulder across the face of the satellite.*

From turbulent, craterless Io to moribund, heavily pocked Callisto, Jupiter's satellites vary because of differences in composition and internal heating, factors largely determined by distance from Jupiter. In other words, what a Jovian moon is like depends on where it is.



where water has welled up from the ocean beneath. Very possibly we would see numerous big ice crystals rising from the ground.

Eventually we would approach the shore of one of Europa's frozen-over continents. Here the silicate base of the moon nears the surface, the crust is more rigid, and the landscape turns a mottled, muddy brown. This more solid ground can still support the ridges and rims of meteorite craters. In other places such craters have sagged into the softer frozen sea. We might also have to climb over smooth mounds of very clear ice a hundred meters high, which run like ribbons through this muddier-looking terrain. These ribbons could be fault lines through which clean ice from below the surface has extruded.

If there are geysers on Europa, they would be almost as unpleasant to walk past as Io's volcanoes. Their ice-pellet fallout would make a stinging sleet storm on earth seem like a gentle rain.

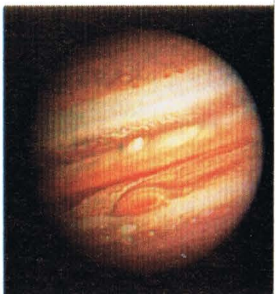
LET'S CONTINUE our moon hop out to big Ganymede, which has considerably more water than Europa. Ganymede's water apparently has frozen to a much greater depth. Trekking across Ganymede would be like crossing a glacier. The surface would crunch beneath our steps. Aeons of micrometeorites have pulverized it into crushed ice.

If we landed on one of the grooved, or raked, blocks on Ganymede's surface, our walk would often be a climb. The grooves may be the valleys in between ice extrusions, or they could be the result of buckling. In any event the effect is chains of ridges a hundred meters high and about ten kilometers apart. After a while, however, this washboard pattern would end abruptly, and we would find ourselves gazing across a vast, ancient muddy brown ice pond covered with the remnants of bygone craters. Even though Ganymede's crust is frozen harder than Europa's, it still cannot support much weight. Therefore the ridges and rims created by meteorites on this older terrain have largely sunk back into the surface.

Why does Ganymede have both old and new terrain? Scientists do not know. But clearly Ganymede was once active enough to create tectonic blocks—icy versions of the drifting continental plates on earth.

At some point its interior must have been stirred enough to cause sections of the original surface to break away and become plates that were later reworked and grooved.

What could have stirred up Ganymede so? The moon might have begun with too much inner heat to shed. However, there's another idea. Since all the Galilean moons always keep the same face toward Jupiter, the master planet's gravity must have "despun" these once fast-



rotating bodies long ago. As Ganymede was despun, the energy in the spin could have warmed the interior, stirring it up enough to move the crust around.

To planetary scientists Ganymede is therefore a grand find. "We may learn more in the long run from Ganymede than from earth about the way plates move," says Larry Soderblom. "Ganymede is a frozen record of tectonism in its naked form."

TECTONISM, however, never surfaced on Callisto, our last stop. Callisto's dark slurry crust probably froze as it formed, and, except for the barrages of meteorites, not much has happened there in the past four and a half billion years.

Crossing Callisto's endless rim-to-rim craters would tax our legs and lungs, were there air to breathe. Callisto's ice mantle froze faster and grew rigid earlier than Ganymede's. It has thus supported meteorite craters and ridges for more years. Consequently its entire surface is rough.

We would head for Callisto's great cataclysmic impact basin. The vista there would reward us for our labor. What an awesome object it must have been that hurtled out of the murk of the infant solar system and made Callisto shudder so. That huge meteorite blasted a hole 200 kilometers across and scores of kilometers deep. Steam must have gushed out from the moon, and briefly Callisto had an ocean. Like a massive, instantly melted glacier, Callisto's ice crust poured into the impact zone and refroze. Today we would find the basin flat but would wander amid a wondrous jumble of icy spikes and jagged protrusions—chunks of the old crust afloat in a frozen morass.

"There's no such thing as a boring Galilean satellite," says Larry Soderblom.

AS THEIR ASTONISHMENT over Voyager's encounters abated, the project's scientists began making more sense of Jupiter's perplexing atmosphere. They concluded, for instance, that the Great Red Spot, the white ovals, and many still smaller spots are all the same type of feature. They are similar to strong high-pressure systems on earth, but larger and much longer lived. They may be one way Jupiter gets heat out of its interior.

Why do Jupiter's cloud features last so long—hundreds of years in some cases? On earth a big hurricane dissipates its energy in a few weeks.

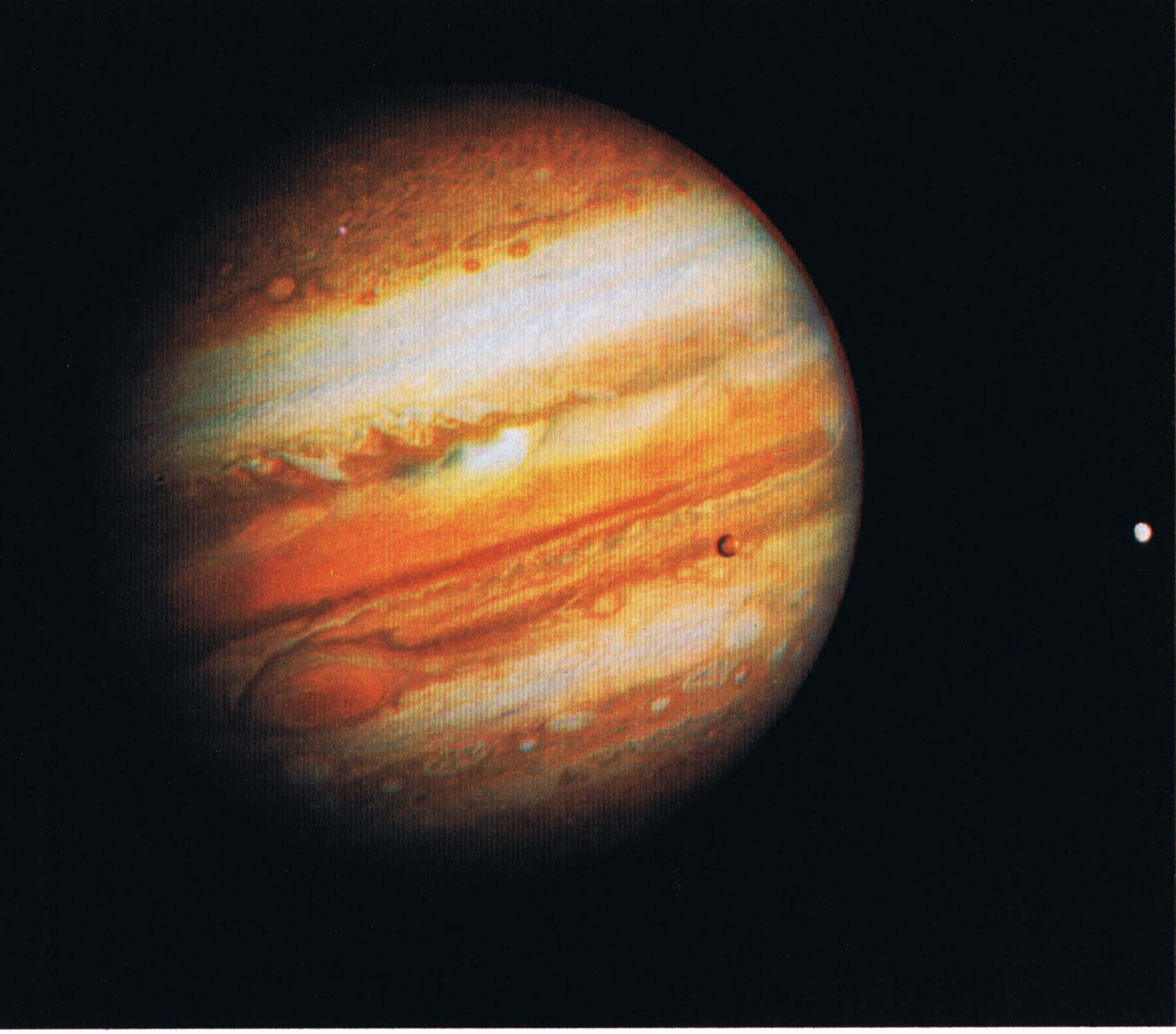
"Jupiter's storms have deep roots, with much more mass. That makes them more stable," suggests Andrew Ingersoll of the California Institute of Technology. "Also, unlike earth, Jupiter has no topography to break up its storms."

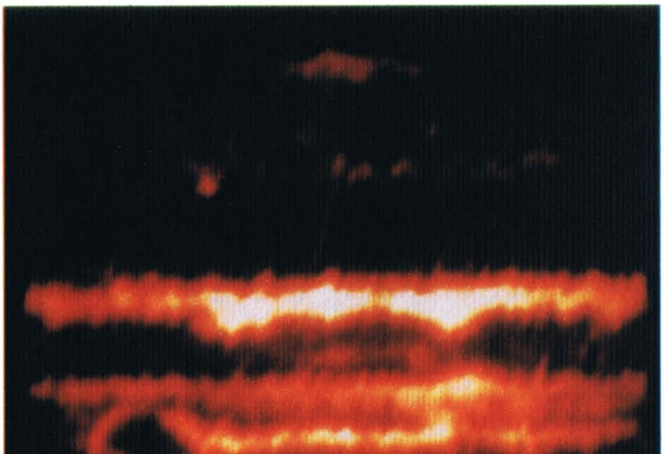
"Jupiter is colder than earth, and cold bodies don't lose energy as readily as warm ones," adds Reta Beebe of New Mexico State University. "Moreover, the materials in Jupiter's cloud cover do not radiate heat as well as water clouds on earth."

Many questions remain about the mechanics of Jupiter's atmosphere. Some of these may be answered in the mid-1980s by a still more sophisticated mission named Galileo. Galileo will shoot a probe deep into Jupiter's atmosphere. The main spacecraft will go into orbit around the planet, taking extreme close-ups of the moons and watching the atmosphere change on a daily basis.

Even Galileo will probably not answer the long-standing question of whether there is life on Jupiter. Voyager's discovery of lightning makes it almost certain that chemical precursors to the molecules of life are being manufactured continually in Jupiter's clouds. The warmer regions of Jupiter's atmosphere are quite similar to that of early earth. One could fantasize about great jellyfishlike creatures lurking in the Jovian clouds. But most scientists believe the atmosphere is too unstable for life. Simple organic chemicals could never have settled in one place long enough to develop into complex biological molecules.

As for the Voyager spacecraft, they will fly past Saturn in November 1980 and August 1981 respectively. If all goes well, Voyager 2 will head on to Uranus for a 1986 encounter, reaching Neptune in 1989. Voyager 1 will sail on out of the solar system without further planetary encounters. Both bear a present from earth, should someone someday in some other solar system find them. They carry dozens of scenes from earth, pictures of human beings, and recordings of terrestrial sounds. Someone somewhere might consider these even more interesting than what Voyager saw. □





TOO SMALL to become a star, too massive to solidify, Jupiter is at the center of a scale-model solar system. Io, on the left, and Europa pass by ***(above)***, their proximity exaggerated by the telephoto lens.

Jupiter is still shedding primordial energy; its hottest areas appear whitish in an infrared image ***(left)*** *taken from earth. And to Voyager it has shed more knowledge than in all the time since Galileo turned his telescope on the night sky in 1610 and discovered four moons of the giant planet.*

What Voyager Saw: Jupiter's Dazzling Realm