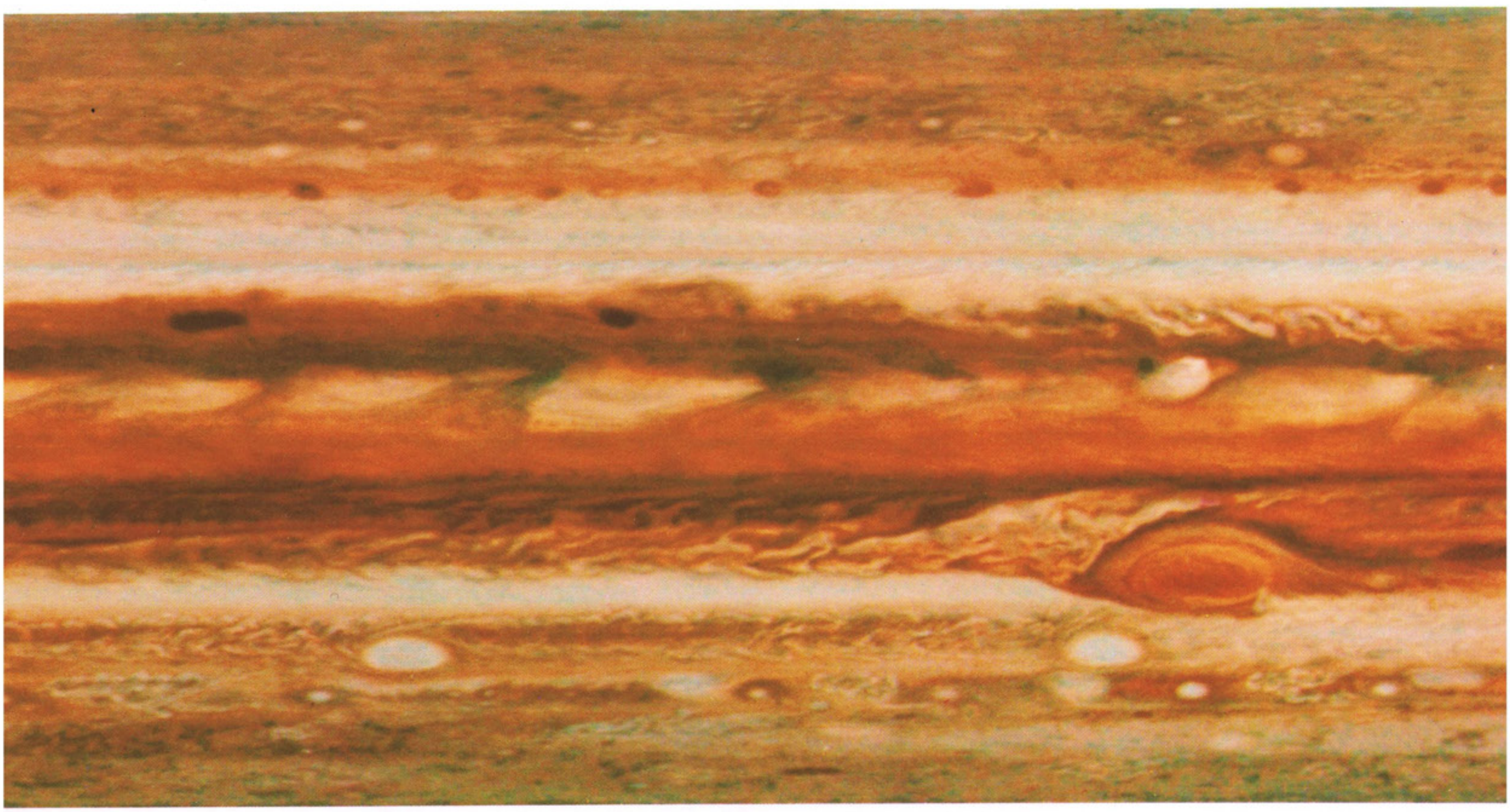
Voyager Encounters Jupiter



COVER: **A cylindrical projection of Jupiter's atmosphere was made from ten color images taken by Voyager 1 during a single ten-hour rotation of the planet.**

A computer-generated mosaic of Voyager 1 pictures showing Jupiter from directly below the south pole. This view shows features as far north as 20 degrees latitude. The black area at the pole results from missing information.

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July 1979

National Aeronautics and
Space Administration


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Foreword

In late summer of 1977, the United States launched two unmanned Voyager spacecraft on an extensive reconnaissance of the outer planets, a decade-long odyssey that could take them to 3 planets and as many as 18 planetary satellites. The first encounter was with the giant Jovian planetary system, 645 million kilometers (400 million miles) away. Passing by Jupiter and its complex satellite system in 1979, the Voyager spacecraft have collected and returned to Earth an enormous amount of data and information that may prove to be a keystone in understanding our solar system.

This publication provides an early look at the Jovian planetary system and contains a selected sample from the more than 30,000 images collected during this phase of the Voyager mission. While Voyager achieved an impressive record of accomplishments, full realization of the scientific value of this program must await the remaining Voyager encounters with Saturn and perhaps Uranus, and a detailed analysis of the data from all the spacecraft investigations.

ROBERT A. FROSCH, *Administrator*
National Aeronautics and Space Administration

Left: A Titan/Centaur rocket served as the launch vehicle for Voyager and was the last planned use of this type of launch vehicle prior to the era of the Space Transportation System (Shuttle Orbiter).

Introduction

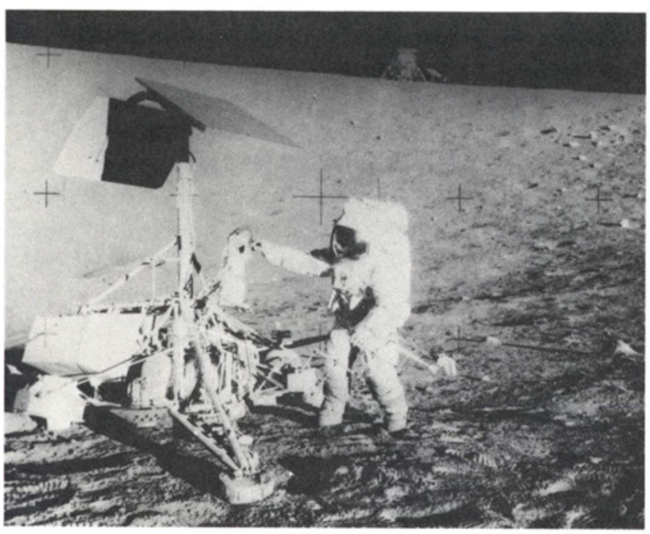
In March 1979 Voyager 1 swept past Jupiter, photographing both the giant planet and five of its moons. Four months later, a companion spacecraft, Voyager 2, made a similar encounter. Now, with Jupiter receding behind them, both spacecraft are headed toward the outer reaches of our solar system. In November 1980, Voyager 1 will fly past Saturn. Voyager 2, traveling at slower speeds, will reach the same way station in August 1981. Beyond there, the itinerary is less certain. In January 1986, eight years after its departure from Earth, Voyager 2 may sail within range of Uranus, taking closeup pictures of that distant planet for the first time. Long after they have exhausted their fuel supplies and their radios have fallen silent, both spacecraft will continue their traverse through space and beyond our solar system, on an endless journey.

Preliminary results of the Voyager encounters with Jupiter are presented in this booklet. As you examine the pictures, you will be participating in a revolutionary journey of exploration. Living in a society where many accomplishments and products are billed as "extraordinary," "stupendous," "once in a lifetime," or "unique," we sometimes lose our perspective. Conditioned to hyperbole, we fail to recognize those advances that are truly exceptional. We need a historian's vantage point to identify the events that can literally change the course of civilization. So it is that every student of history recognizes the importance of the Renaissance, an extraordinary time when man looked outward, reaching beyond the traditions of the past to study his place in the natural world. The results were apparent in art, architecture, and literature, in new philosophic and governmental systems, and in the staggering scientific revolution exemplified by Galileo's first examination of the heavens with a telescope, and in his stubborn support of the heretical assertion that the Earth was *not* the center of the solar system.

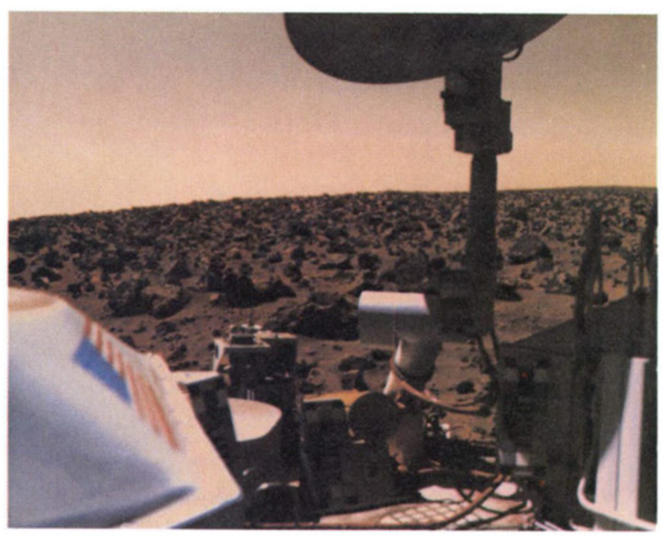
Historians writing a hundred or two hundred years from now may well look on the latter part of the twentieth century as another turning point in civilization. For the first time, we explored beyond Earth—first the Moon, then the neighboring planets, and finally the outermost planets, the very fringe of our solar system.

How will the historian evaluate this period of exploration? First, perhaps, he will describe the Apollo program as a visionary example of great cooperative ventures that can be accomplished by many individuals, private companies, and government institutions. He will describe the subsequent space ventures that weave a fabric of cooperation and goodwill between nations.

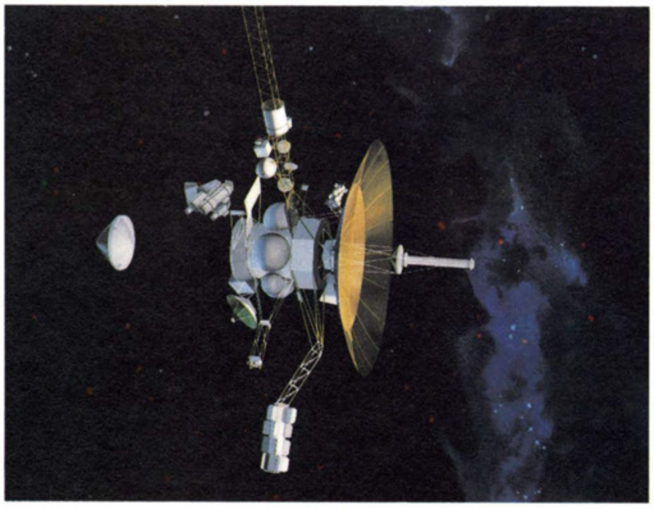
He will point out the technological advances incorporated in unmanned spacecraft, sophisticated robots able to control their own activities and solve their own problems. He will mention the revolution in microelectronics—the art of fabricating complex electrical control circuits so small the eye cannot perceive them, a revolution accelerated by the requirement to conserve weight and generate performance in interplanetary spacecraft. He will point to the introduc-



An Apollo 12 astronaut retrieves Surveyor 3 hardware for Earth laboratory analysis after 30 months exposure on lunar surface.



Viking Lander 2 surveys the boulder-strewn Utopian Plain and reddish sky of Mars.



Galileo orbiter and probe mission to Jupiter in 1985 will expand upon the Voyager investigations of the Jovian system.

A solar electric propulsion spacecraft would eject an instrumented probe toward Halley's comet in 1986 and continue on to rendezvous with another comet, Tempel 2.

tion of new products, particularly in areas of communication, medical treatment, and energy conversion.

Turning his attention to the environment, the historian will almost surely suggest that the first widespread realization of the fragile natural balances on Earth came at a time when we were first able to see our Earth in its entirety. The impact of a picture of Earth from deep space, a luminously blue globe surrounded by darkness, has probably been more persuasive than lengthy treatises describing the complex ways in which our system of rocks, plants, animals, water, and air is interrelated. On a more practical level, the historian will point to the new understanding of our terrestrial environment. The composition and structure of other planetary atmospheres—on Venus, Mars, and Jupiter—provide important clues to what may happen in our own atmosphere, especially if we disrupt the chemical composition. Study of the primitive crusts of the Moon, Mars, and Mercury permits us to reconstruct the first billion years of Earth history, a time when chemical elements were being concentrated in activity ultimately leading to the formation of important ore deposits. Unmanned spacecraft missions to the Sun increase our understanding of that most fundamental of all energy sources, paving the way for the efficient conversion of solar energy into many practical applications, and releasing us from dependence on ever-decreasing reserves of fossil fuels. Spacecraft circling the Earth study the upper atmospheric processes that play major roles in controlling our weather. These same spacecraft look down on Earth, aiding us with increasingly accurate forecasts of weather and crop productivity.

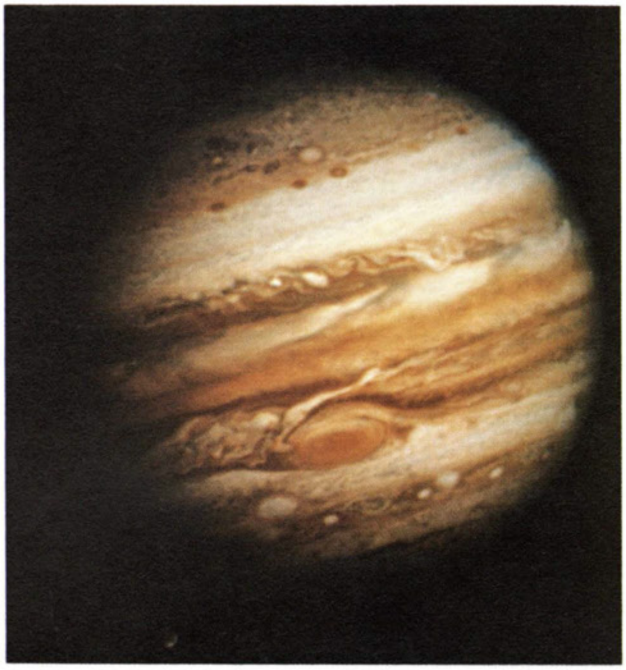
Looking beyond matters of technology and the environment, the historian may cite the latter part of the twentieth century as a time of explosive exploration, comparable to the 15th and 16th century exploration of the Earth's oceans and the distant lands that bounded them. In a sense, exploration—whether it is physical or intellectual—provides its own rewards. The United States has always been a nation that moves forward, pushing back the frontiers of the West, pushing back the frontiers of social and economic development, and now pushing back the frontiers of space. It is arguable that this spirit of exploration is indispensable to a vigorous society, and that any society that ceases to explore, to inquire, and to strive is only a few years from decline.

And so the historian may recall the early days of lunar exploration, the Apollo project, the landing of unmanned Viking spacecraft on Mars, and the encounters of Voyager spacecraft with Jupiter and Saturn as the first steps in a sustained program of space exploration—a program that is profoundly changing man's perspective of himself, of the Earth, and of the larger cosmos beyond.

THOMAS A. MUTCH, *Associate Administrator for Space Science*
National Aeronautics and Space Administration

Images of Jupiter and Its Satellites

2/5/79 28.4 million km (17.6 million r



1/24/79 40 million km (25 million mi)

5/9/79 46.3 million km (28.7 million mi)

Jupiter's atmosphere is undergoing constant change, presenting an ever-shifting face to observers. The Great Red Spot has undergone three major periods of activity in the last 15 years. These images of Jupiter, taken by Voyager 1 (top) and Voyager 2 (bottom) almost four months apart, show that cloud movement in the Jovian atmosphere is not uniform because wind speeds vary at different latitudes. For example, the white ovals which appear below the Great Red Spot dramatically shifted between January and May, the time interval between these two pictures. The bright "tongue" extending upward from the Great Red Spot interacted with a thin, bright cloud above it that had traveled twice around Jupiter in four months. Eddy patterns to the left of the Great Red Spot, which have been observed since 1975, appear to be breaking up.

◁ **Jupiter** is the largest planet in our solar system, with a diameter 11 times that of Earth. Jupiter rotates very quickly, making one full rotation in just under ten hours. Composed primarily of hydrogen and helium, Jupiter's colorfully banded atmosphere displays complex patterns highlighted by the Great Red Spot, a large, circulating atmospheric disturbance. Three of Jupiter's 13 known satellites are also visible in this Voyager 1 photograph.The innermost large satellite, Io, can be seen in front of Jupiter and is distinguished by its bright, orange surface. To the right of Jupiter is Europa, also very bright but with fainter surface markings. Callisto is barely visible beneath Jupiter. These satellites orbit Jupiter in the equatorial plane and appear in their present position because Voyager is above the plane.

The date of each photograph and the distance of the spacecraft from the planet or satellite are included with each picture.

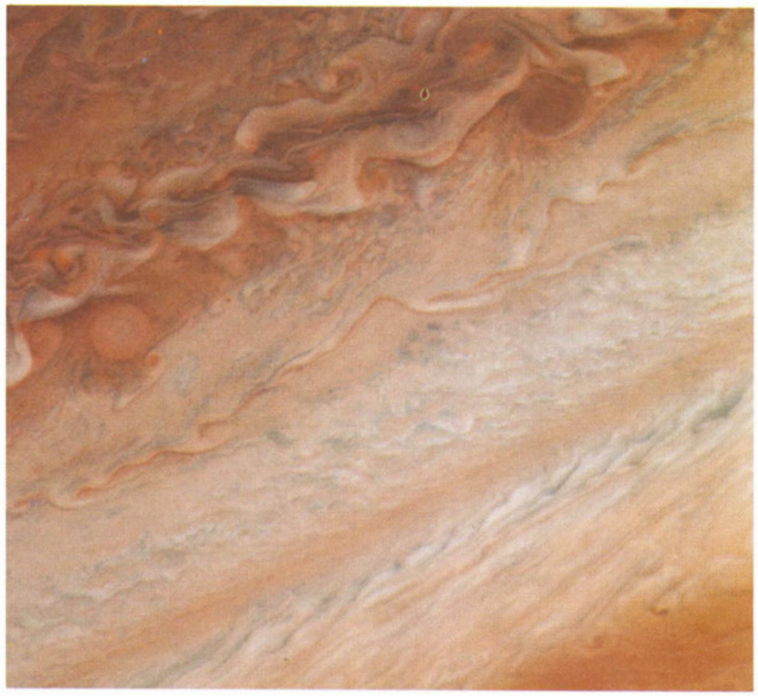
2/25/79 9.2 million km (5.7 million mi)

The Great Red Spot on Jupiter is a tremendous atmospheric storm, twice the size of Earth, that has been observed for centuries. The Great Red Spot rotates counterclockwise with one revolution every six days. Wind currents on the top flow east to west, and currents on the bottom flow west to east. This Voyager 1 picture shows the complex flow and turbulent patterns that result from the Great Red Spot's interactions with these flows. The large white oval is a similar, but smaller, storm center that has existed for about 40 years.

7/3/79 6 million km (3.72 million mi)

A comparison of the Voyager 2 photograph above with the preceding Voyager 1 photograph shows several distinct changes in the Jovian atmosphere around the Great Red Spot. The white oval beneath the Great Red Spot in the first picture has moved farther around Jupiter, and a different white oval has appeared under the Great Red Spot in the Voyager 2 picture taken four months later. The disturbed cloud regions around the Great Red Spot have noticeably changed, and the white zone west of the Great Red Spot has narrowed.

High-speed wind currents in the mid-latitudes of Jupiter are shown in this high-resolution Voyager 1 photograph. The pale orange line running diagonally to the upper right is the high-speed north temperate current with a wind speed of about 120 meters per second (260 miles per hour), over twice as fast as severe hurricane winds on Earth. Toward the top of the picture, a weaker jet of approximately 30 meters per second (65 miles per hour) is characterized by wave patterns and cloud features that rotate in a clockwise manner.



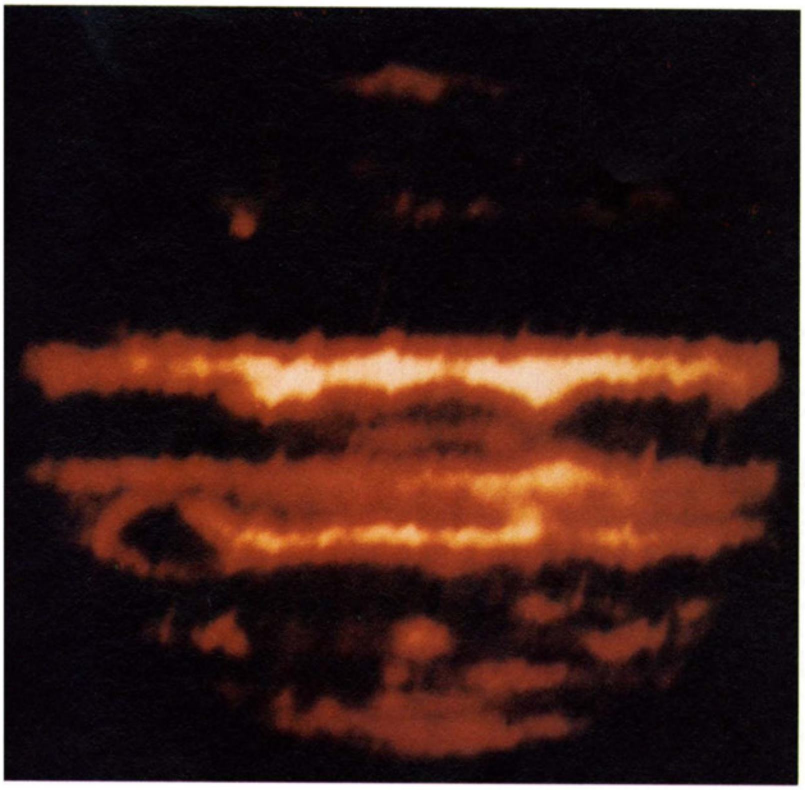
3/2/79 4 million km (2.5 million mi)

The large brown-colored oval appearing in this Voyager 1 picture was selected as one of the targets to be photographed near closest approach to Jupiter because it is probably an opening in the upper cloud deck that exposes deeper, warmer cloud levels. Brown ovals (which can also be seen in the photographs above and on the next page) are common features in Jupiter's northern latitudes and have an average lifetime of one to two years.

3/2/79 4 million km (2.5 million mi)

Jupiter's Equatorial Zone is the broad, orange band that traverses the center of this Voyager 2 picture. This zone is characterized by the wispy clouds along its northern edge. The brown oval was observed by Voyager 1 four months earlier, illustrating the stability of this type of feature in the Jovian atmosphere. In contrast, the turbulent region in the lower right of the picture, which lies just to the left of the Great Red Spot, shows features that are relatively short lived. With the exception of the cooler Great Red Spot, as colors range from white to orange to brown, we are generally looking at deeper and warmer layers in the Jovian atmosphere.

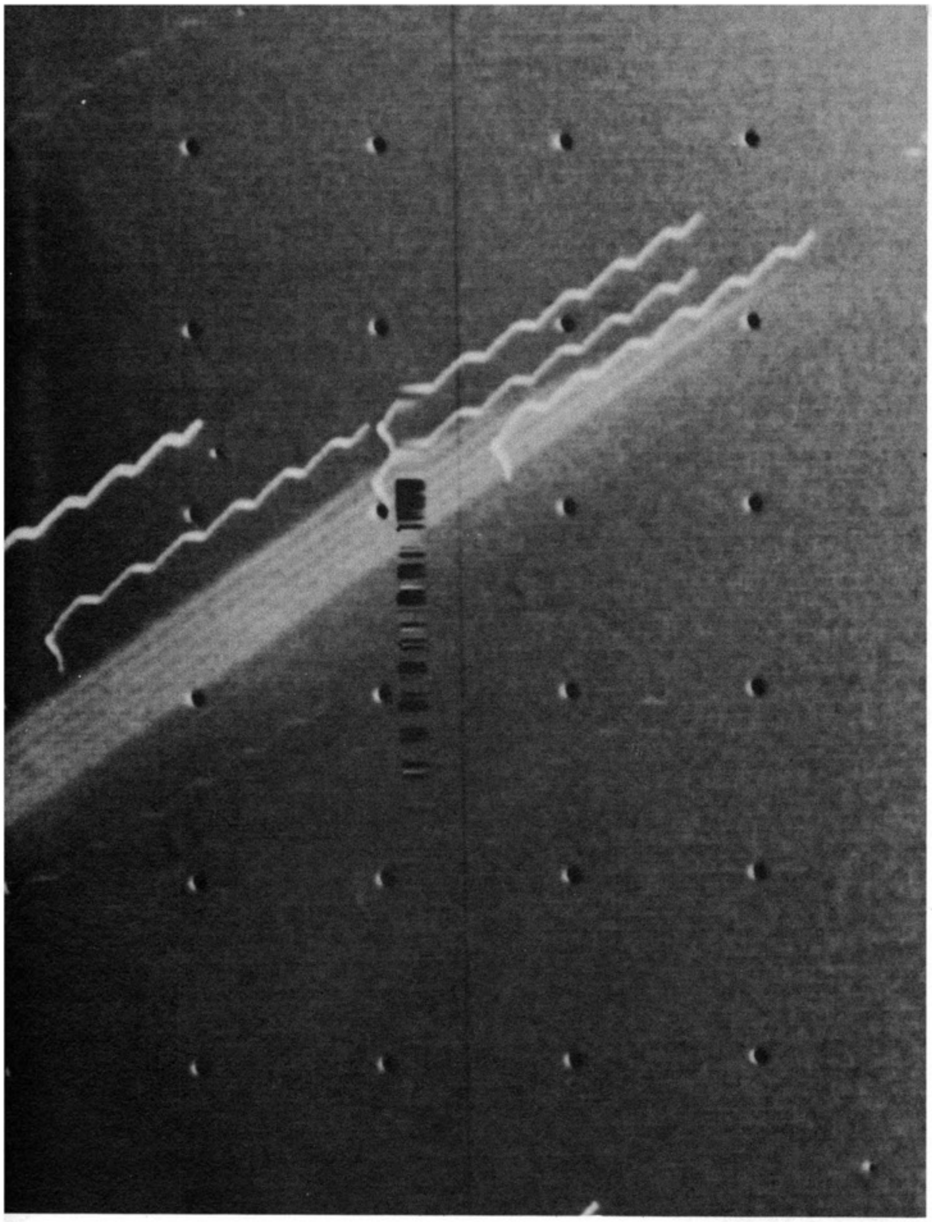
'28/79 10.3 million km (6.4 million mi)



1/10/79 535 million km (332 million mi)

The infrared image of Jupiter on the left was taken from Earth and shows heat radiating from deep holes in Jupiter's clouds. Bright areas in the image are higher temperature regions than the dark areas and correspond to parts of the atmosphere that are relatively free of obscuring clouds. The Great Red Spot appears on the left limb, or edge of the planet, as a dark area encircled by a bright ring, indicating that the Spot is cooler than the surrounding region. The infrared image was recorded by the 200-inch Hale telescope on Mount Palomar in California. The Voyager 1 picture on the right was also taken the same day, about one hour after the infrared image.

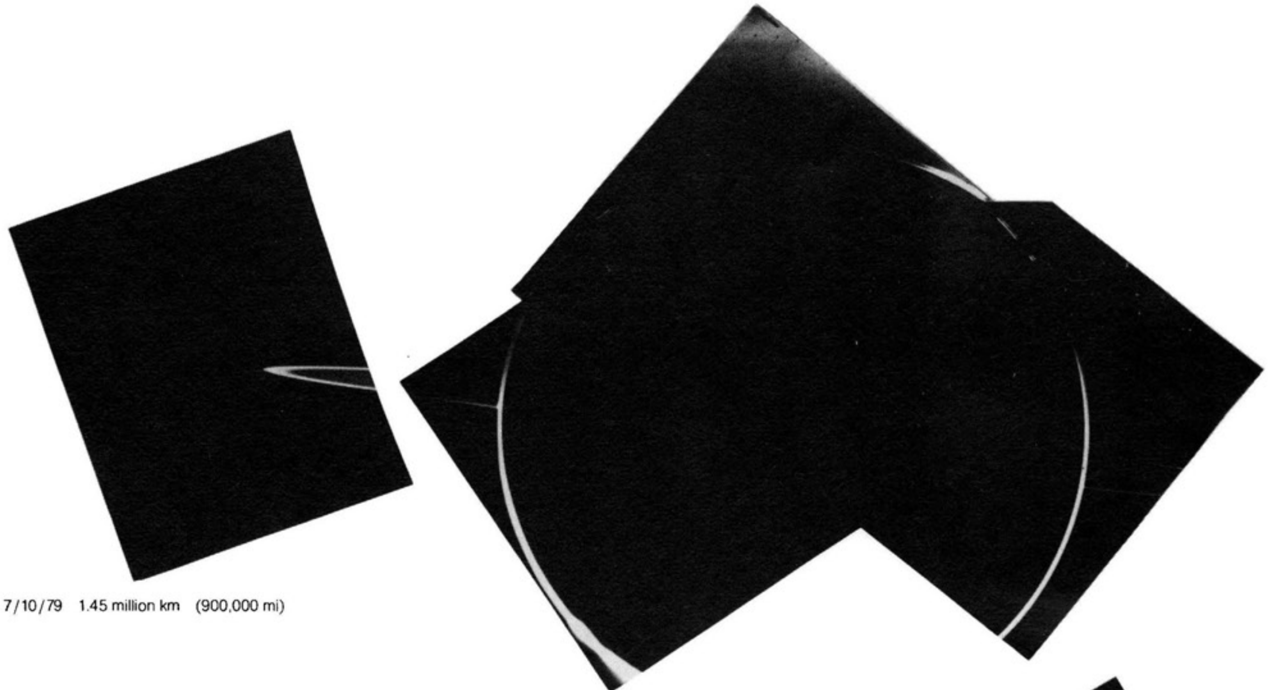
The largest aurora ever observed, nearly 29,000 kilometers (18,000 miles) long, appears in this Voyager 1 photograph, taken on the dark side of Jupiter six hours after closest encounter. The auroral lights are brighter than any northern lights seen on Earth. Jupiter's north pole is approximately midway along the auroral arc. This timed exposure of the aurora also shows what appear to be lightning storms several thousand kilometers below the aurora. The strength of the lightning bolts is comparable to that of superbolts seen near cloud tops above Earth. Lightning had been suspected to exist on Jupiter, but at lower levels in the atmosphere.



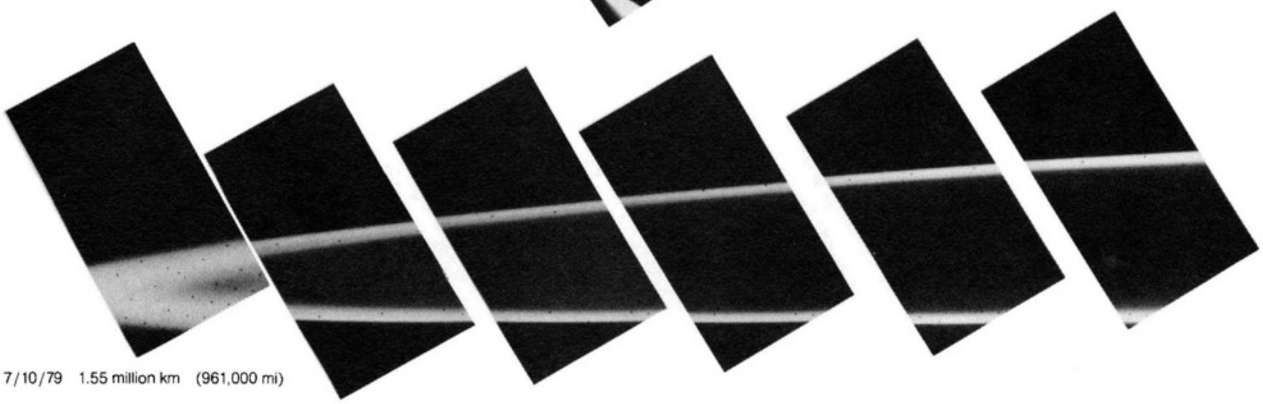
3/4/79 1.2 million km (750,000 mi)

The first evidence of a ring around Jupiter is seen in this photograph taken by Voyager 1. This photograph was part of a sequence planned to search for such rings around Jupiter. The multiple image of the extremely thin, faint ring appears as a broad light band crossing the center of the picture. This multiple image and the elongated, wavy motion of the background stars are due to the 11-minute, 12-second exposure and the very slow natural oscillation of the spacecraft. The ring, which is in Jupiter's equatorial plane, is invisible from Earth because of its thinness and transparency and because of Jupiter's brightness. The black dots in the picture are calibration points in the camera.

Because of Voyager 1's discovery of a ring around Jupiter, Voyager 2 was programmed to take additional pictures of the ring. The three Voyager 2 images on the next page show Jupiter's ring in progressively higher resolution. The pictures were taken when Jupiter was eclipsed by the Sun, and the ring appears unusually bright because of the forward scattering of sunlight by small ring particles. In the top four-picture mosaic, the arms of the ring curving toward the spacecraft (on the near side of the planet) are cut off by the planet's shadow. Scientists estimate that the distance from the Jovian cloud tops to the outer edge of the ring is 55,000 kilometers (35,000 miles). In the center picture, which is composed of six images, there is evidence of structure within the ring, but the spacecraft motion during these long exposures obscured the highest resolution detail. However, there is speculation that the ring width, estimated at 6000 kilometers (4000 miles), contains more than one ring. The bottom photograph is an enlargement of the isolated left frame in the first picture and reveals a density gradient of very small particles extending inward from the ring. The thickness of the ring has been estimated at less than one kilometer (0.6 mile) although the ring appears about 30 kilometers (19 miles) thick in the image, due to camera motion and finite resolution. Composition of the low-albedo (dark) particles is not known, but particle size probably ranges from microscopic to at most a few meters in diameter. If collected together to form a single body, the total mass of the Jovian rings would form an object with a diameter less than twice that of tiny Amalthea.



7/10/79 1.45 million km (900,000 mi)



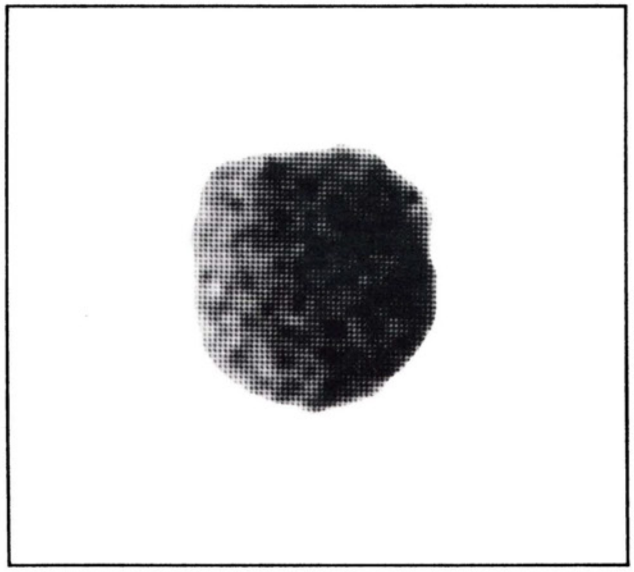
7/10/79 1.55 million km (961,000 mi)

7/10/79 1.45 million km (900,000 mi)

2/13/79 20 million km (12.4 million mi)

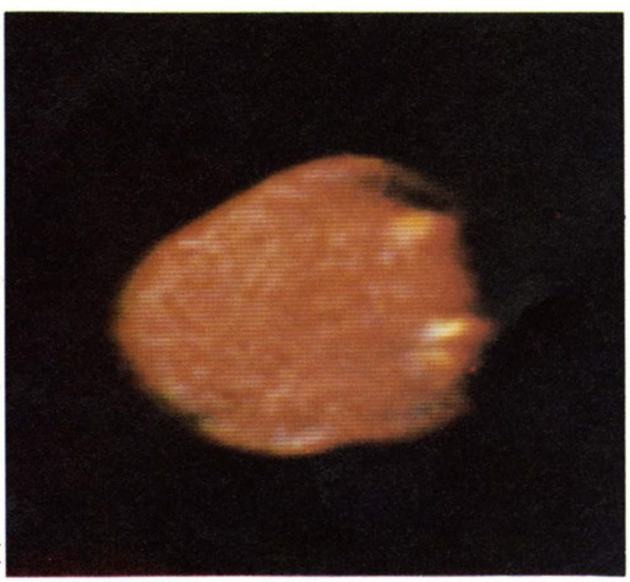
Jupiter and two of its planet-sized satellites, Io at left and Europa at right, are visible in this Voyager 1 picture. Jupiter's four largest satellites—Io, Europa, Ganymede and Callisto—were discovered in 1610 by Galileo Galilei. The two outer Galilean satellites are Ganymede and Callisto, not shown in this picture. All four satellites probably formed about four billion years ago but their surfaces vary in age tremendously. Io and Europa have younger, more active surfaces than Ganymede and Callisto. Like our Moon, the satellites keep the same face toward Jupiter. In this picture, the sides of the satellites that always face away from the planet are visible.

3/4/79 1.25 million km (780,000 mi)



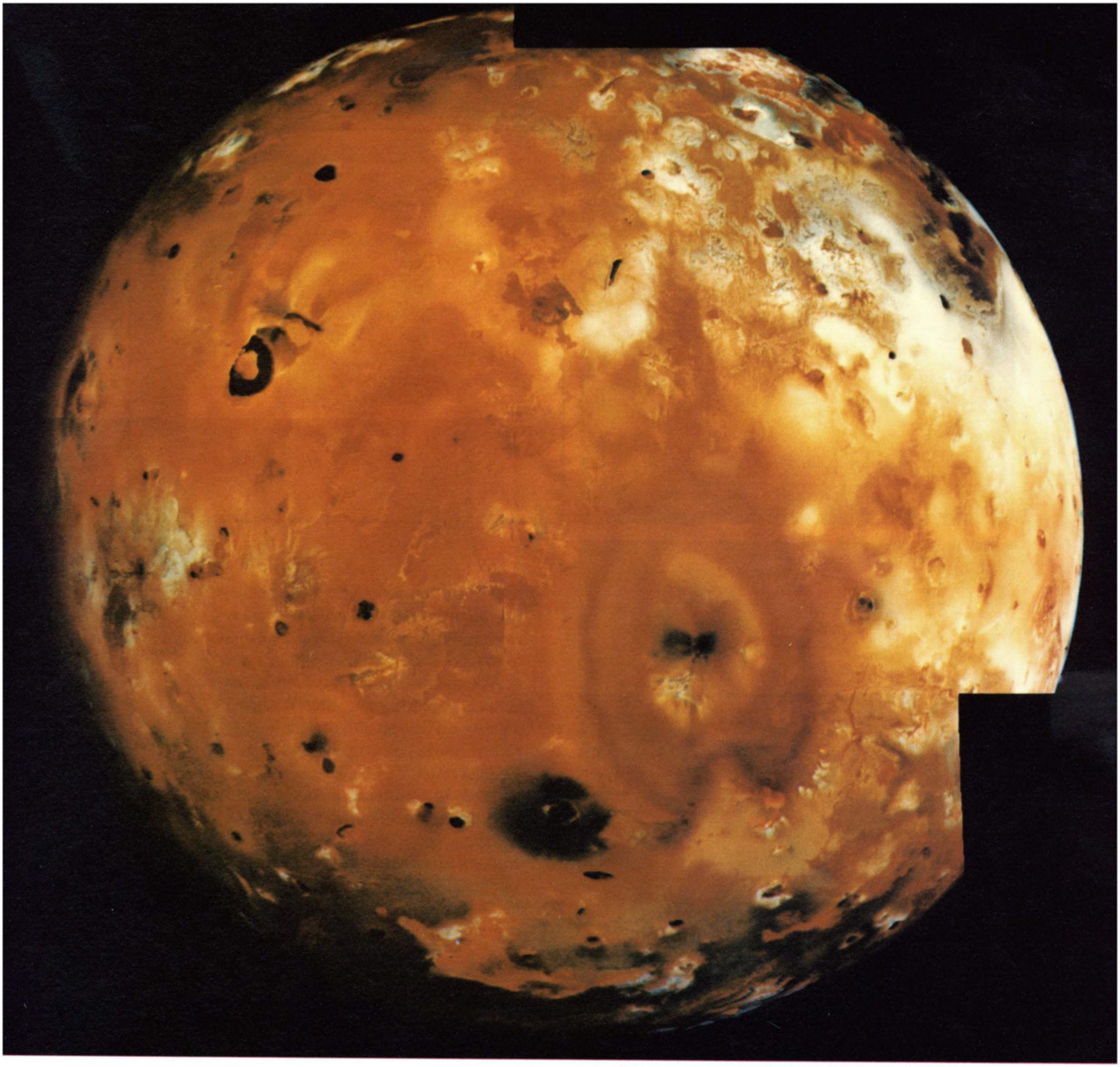
7/9/79 560,000 km (350,000 mi)

3/4/79 695,000 km (430,000 mi)



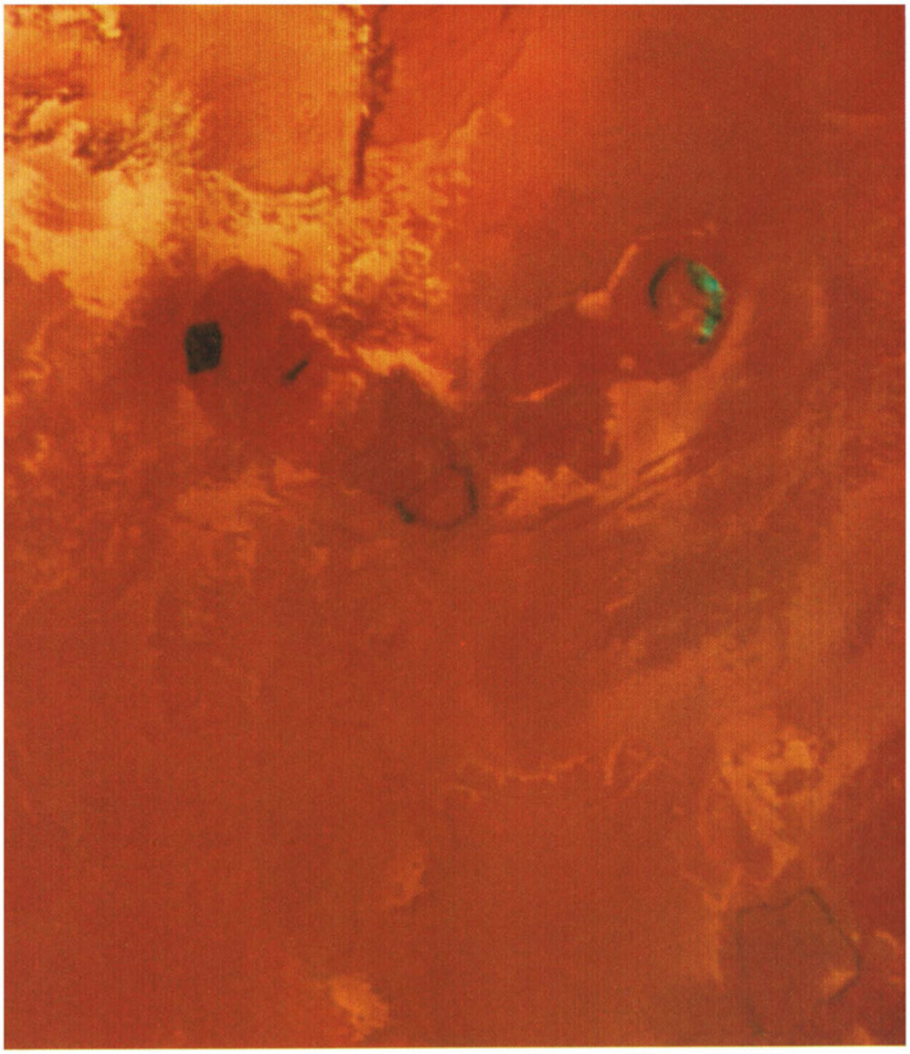
3/5/79 425,000 km (264,000 mi)

Amalthea, Jupiter's innermost satellite, was discovered in 1892. It is so small and close to Jupiter that it is extremely difficult to observe from Earth. Amalthea's surface is dark and red, quite unlike any of the Galilean satellites. The three Voyager 1 pictures on the left and the one Voyager 2 picture above (seen against the disk of Jupiter) reveal a small, elongated object, about 265 kilometers (165 miles) long and 150 kilometers (90 miles) in diameter. Amalthea keeps its long axis pointed toward Jupiter as it orbits around the planet every 12 hours. Amalthea was observed end-on in the Voyager 2 picture, which has been computer-processed to enhance the image.



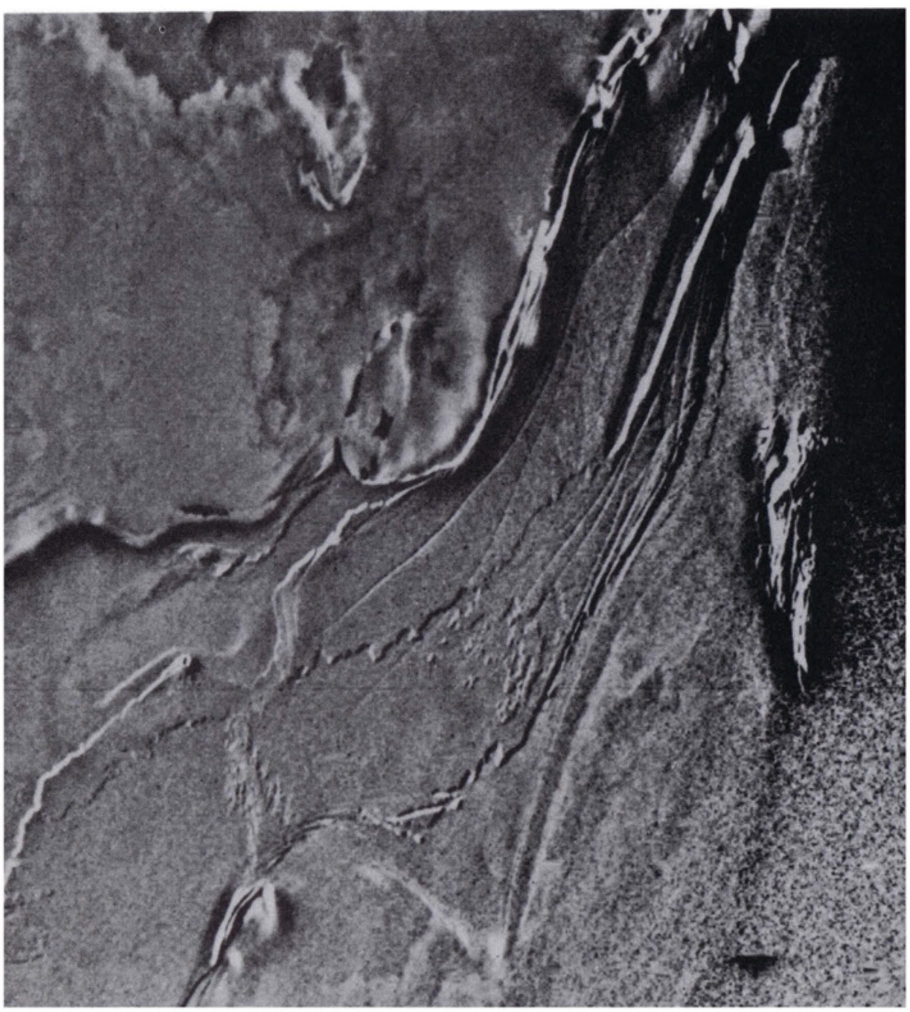
3/4/79 377,000 km (234,000 mi)

Io, Jupiter's innermost Galilean satellite, displays great diversity in color and brightness. This Voyager 1 four-picture mosaic shows Io's complex coloration of red-orange, black, and white regions, and the two major topographic features: volcanic regions, the most prominent of which is the "hoofprint" (volcanic deposition feature) in the center-right, and the intervolcanic plains that are relatively featureless. Io's vivid coloring is probably due to its composition of sulfur-rich materials that have been brought to the surface by volcanic activity.



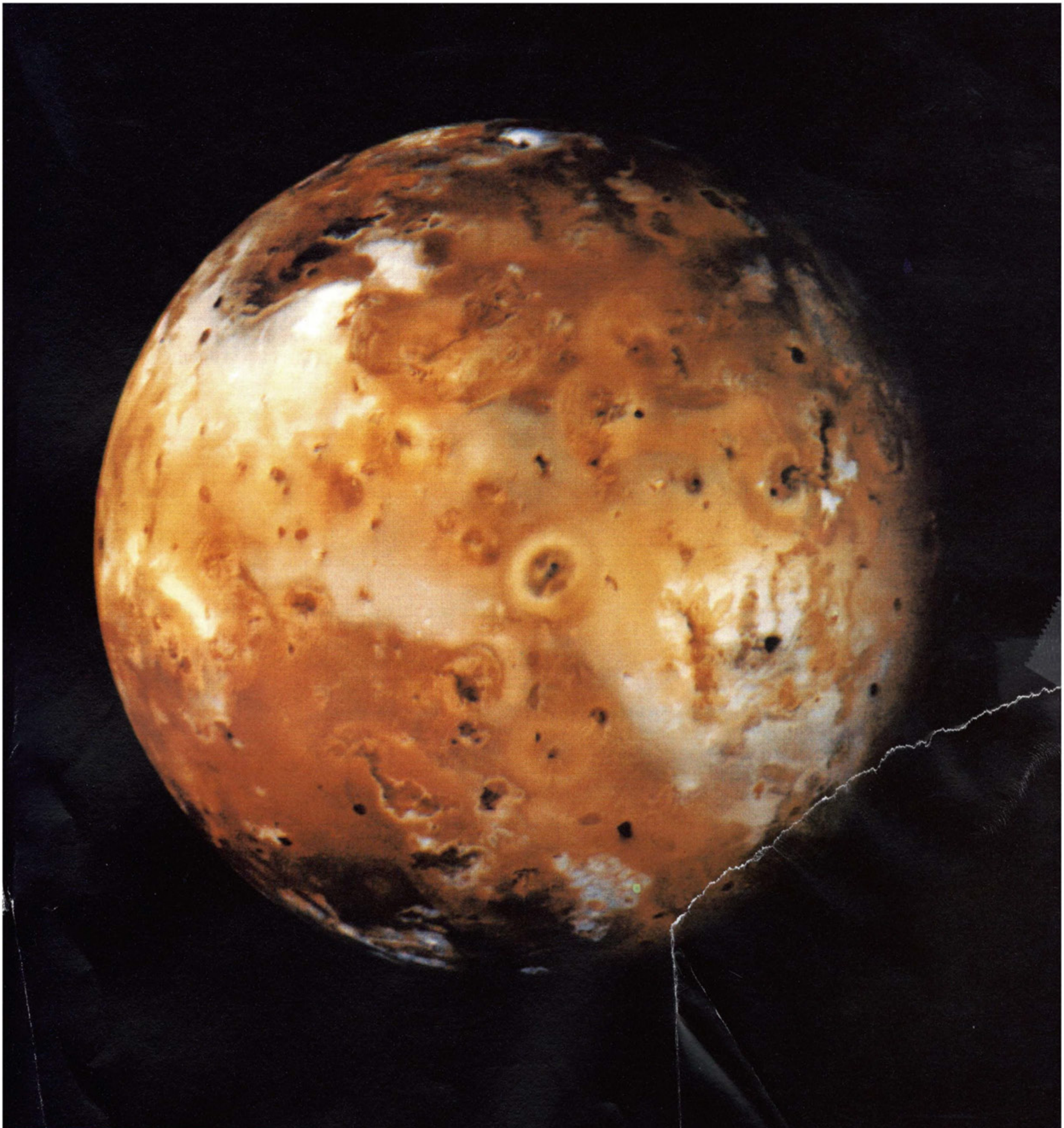
3/5/79 129,600 km (80,500 mi)

The bright area at the upper right in this Voyager 1 picture of Io appears to be a caldera (collapsed volcano) that is venting clouds of gases. The clouds may condense to form extremely fine particles that scatter light and appear blue. Because the infrared spectrometer discovered sulfur dioxide on Io, scientists believe this gas may be the main component of the clouds. Sulfur dioxide clouds would rapidly freeze and snow back to the surface. It is also possible that dark areas in the floors of the calderas are pools of encrusted liquid sulfur.



3/5/79 66,000 km (41,000 mi)

Evidence of erosion in Io's southern polar region is visible in this Voyager 1 high-resolution image. The picture has been computer-enhanced to bring out surface detail while suppressing bright markings. A depressed segment of the crust, bounded by faults, is seen near the terminator in the upper right portion of the image. At the lower center are complicated scarps (slopes) and portions of isolated elevated terrain that geologists interpret as "islands" left behind as the scarps eroded. Scientists speculate that sulfur dioxide (as a subsurface liquid) may be a determinant in the creation of these features.



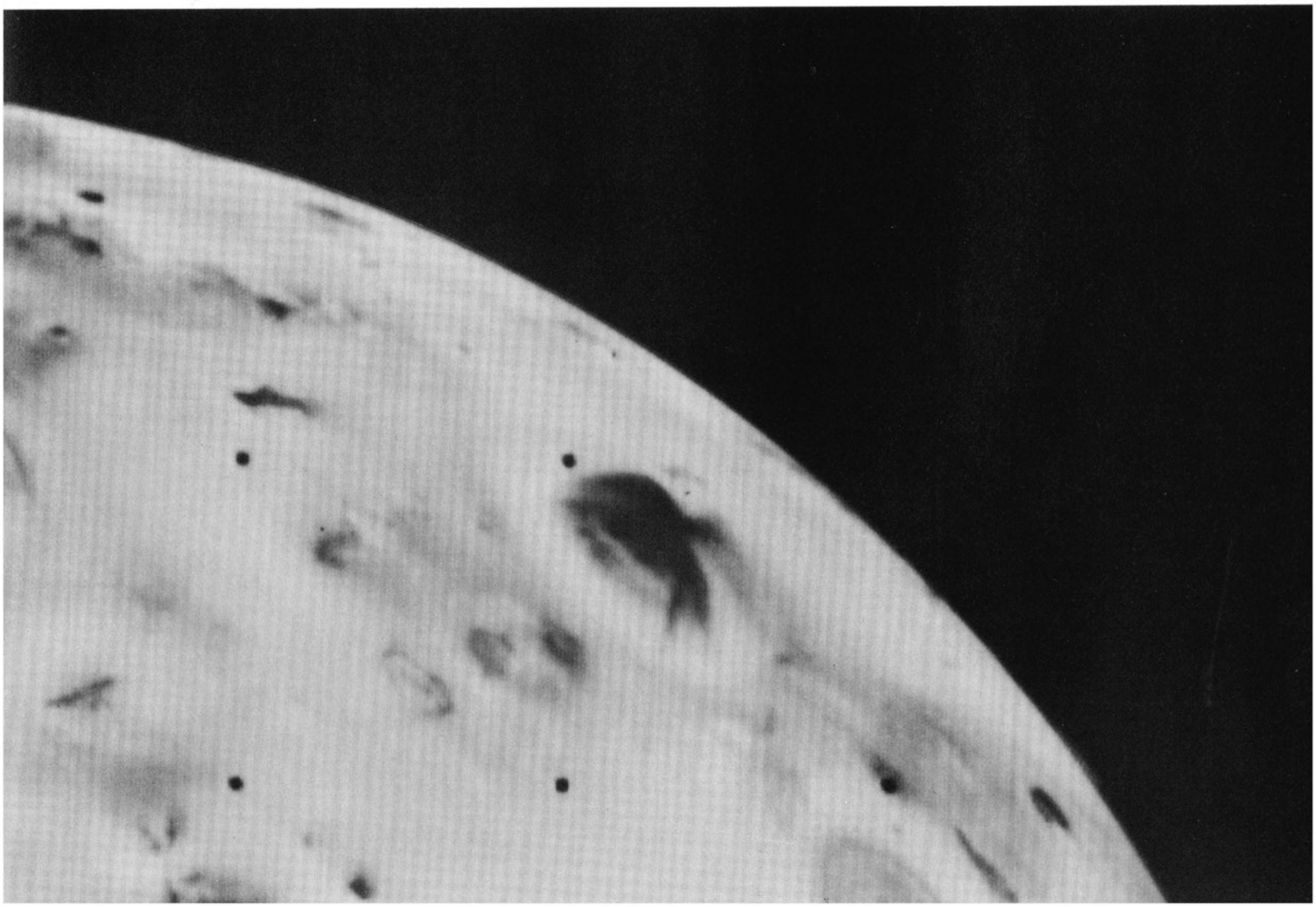
3/4/79 862,000 km (540,000 mi)

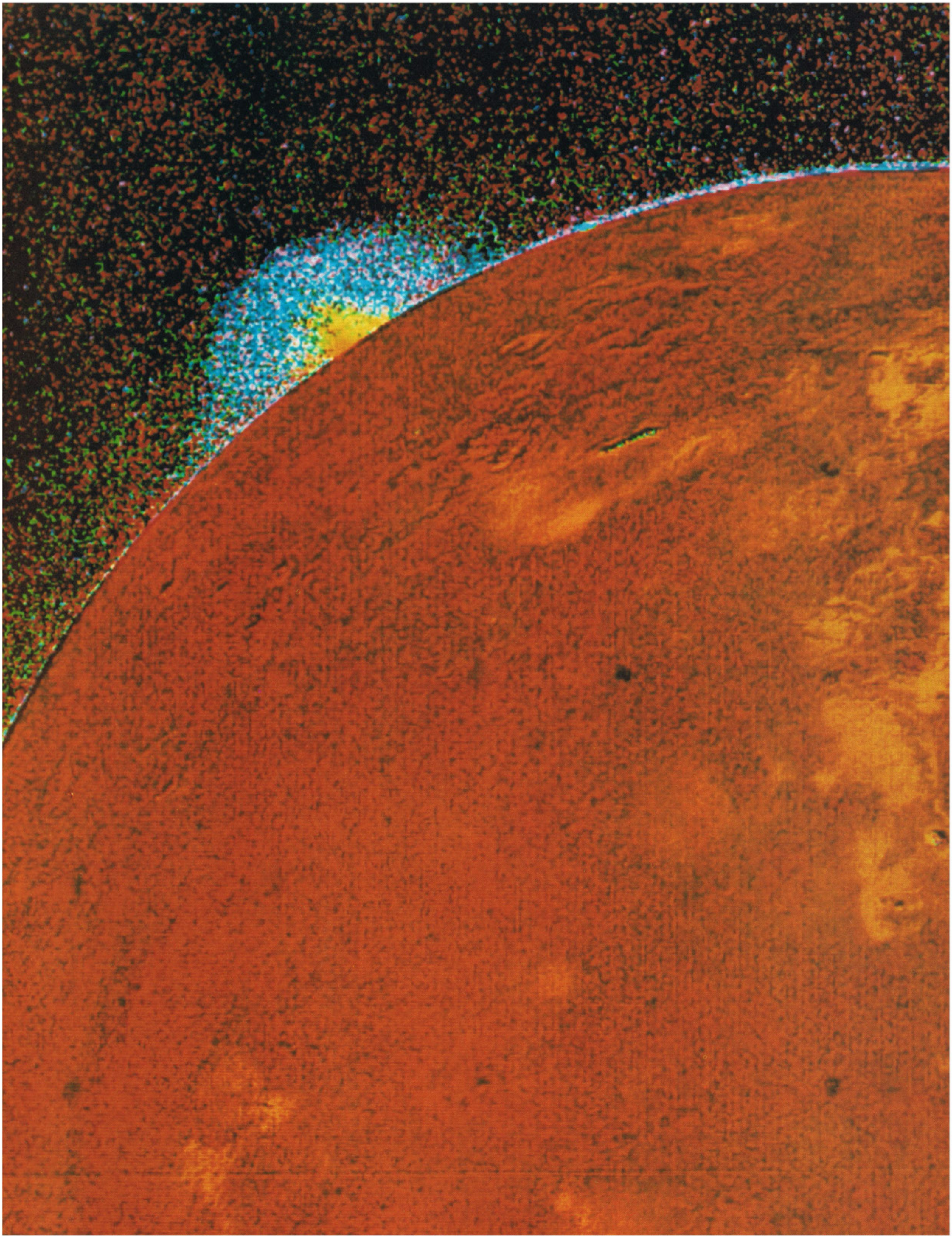
Io's surface, less than ten million years old, is quite young compared to the other Galilean satellites and to other terrestrial bodies, such as Mercury and the Moon. The surface is composed of large amounts of sulfur and sulfur dioxide frost, both of which account for most of the surface color. This picture was taken by Voyager 1.

The first active volcanic eruptions other than on Earth were discovered on Io. These volcanoes are extremely explosive with ejection velocities of more than one kilometer per second (2200 miles per hour), which is more violent than Etna, Vesuvius, or Krakatoa on Earth. In the top picture, the plume visible on the right edge extends more than 100 kilometers (60 miles) above the surface. The same volcano is shown in the lower picture, photographed one hour and 52 minutes earlier. Both pictures were taken by Voyager 1. On the preceding page, the material deposited by the volcano can be seen as a white ring near the center of Io.

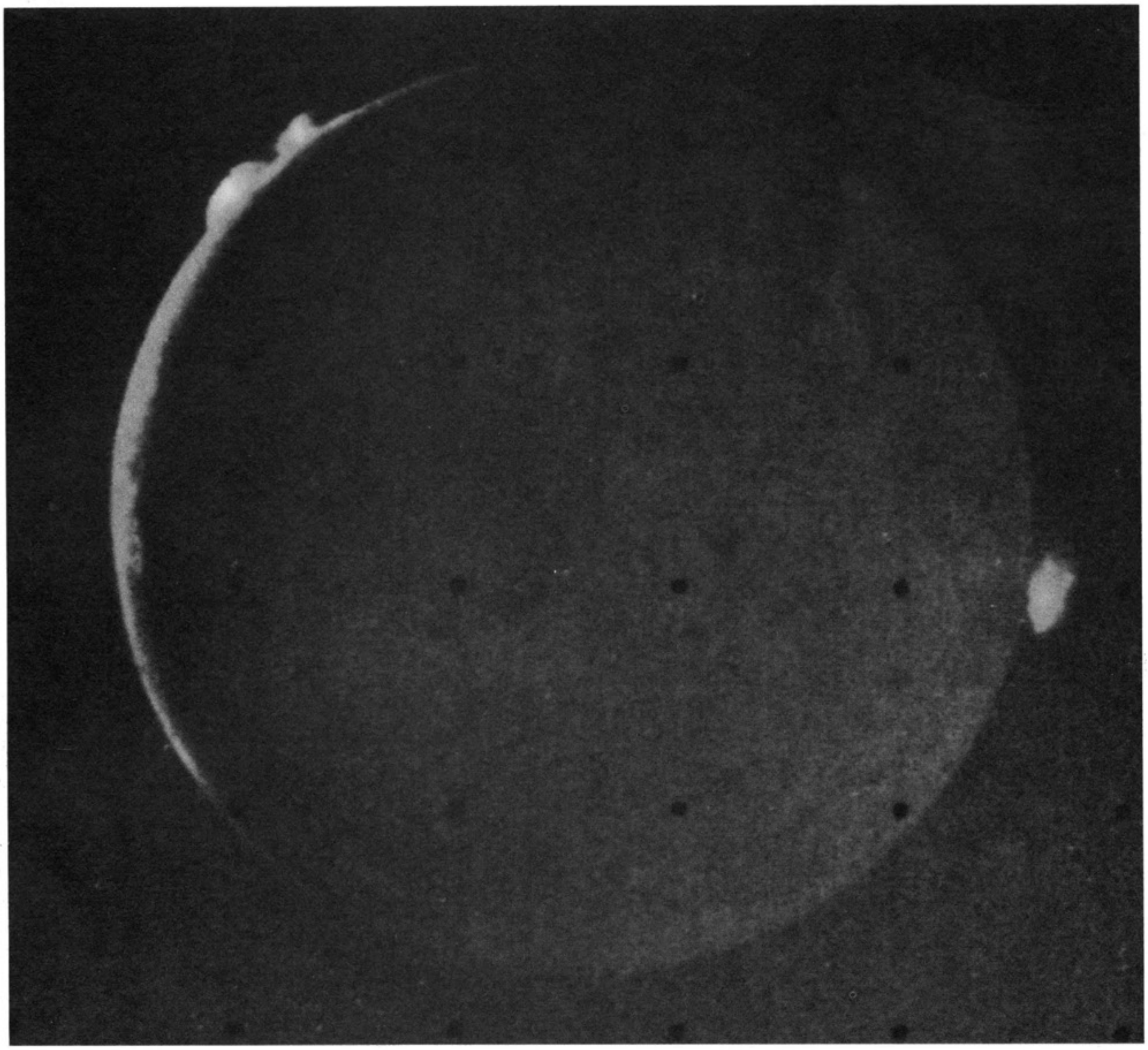
3/4/79 450,000 km (280,000 mi)

3/4/79 499,000 km (310,000 mi)





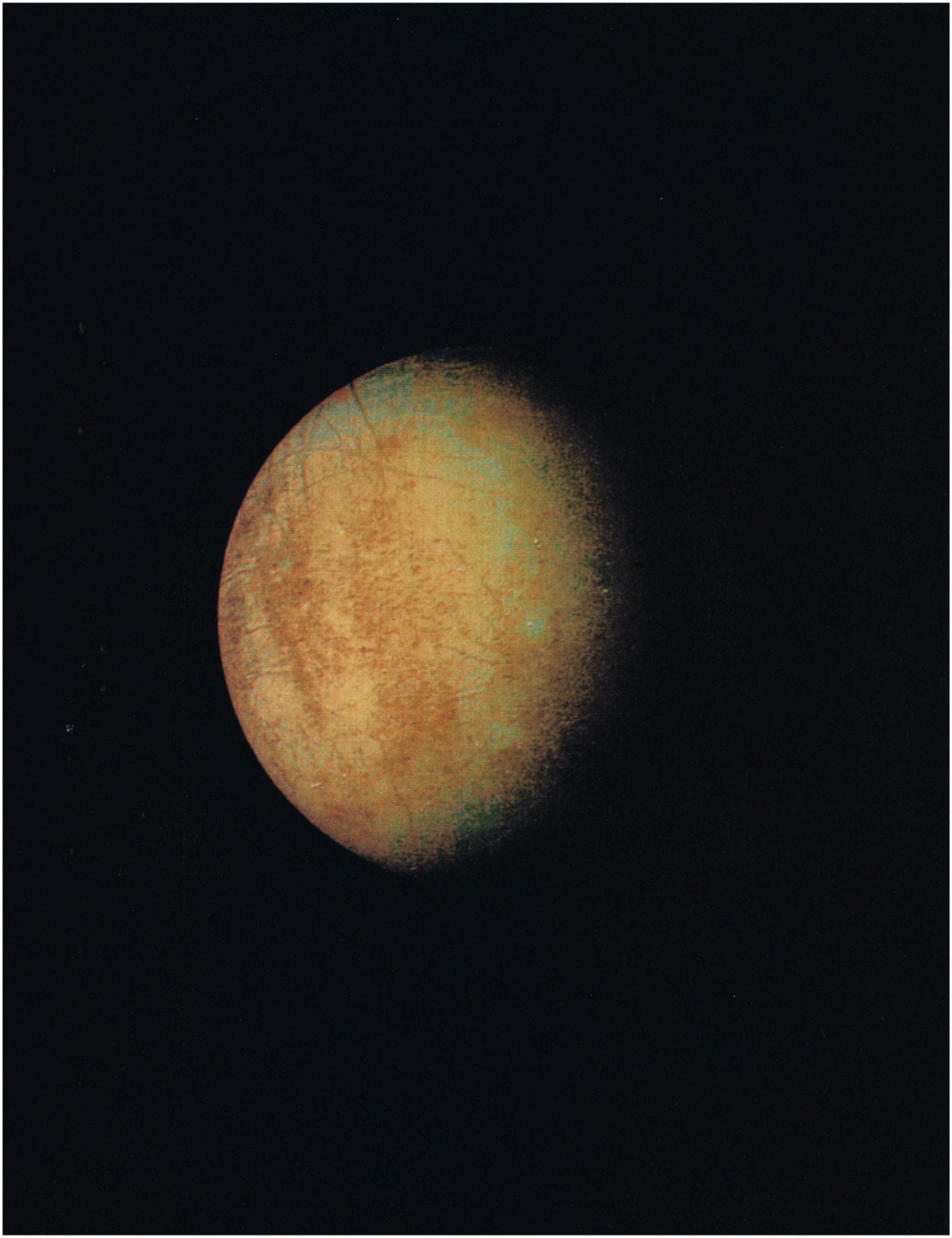
7/10/79 1.2 million km (750,000 mi)



Of the eight active volcanoes discovered on Io by Voyager 1, six of the seven volcanoes sighted by Voyager 2 were still active. The giant volcano observed by Voyager 1 over the "hoofprint" region (see page 18) had become inactive. Scientists, therefore, believe that the satellite is undergoing continuous volcanic activity, making Io's surface the most active in the solar system. This Voyager 2 photograph, which shows three active volcanoes, was one of the last of an extensive sequence of "volcano watch" pictures planned as a result of Voyager 1's volcano discovery. The black dots are calibration points on the camera.

◁ **Special color reconstruction** by means of ultraviolet, blue, green, and orange filters allowed scientists to study the amount of gas and dust and the size of the dust particles that erupted from the volcano on Io shown in this Voyager 1 image. The region that is brighter in the ultraviolet (blue area) is about 210 kilometers (130 miles) high, over twice the height of the denser, bright yellow core. The vent area is visible on page 18 as a dark ring in the upper left region of Io.

3/4/79 490,000 km (304,000 mi)

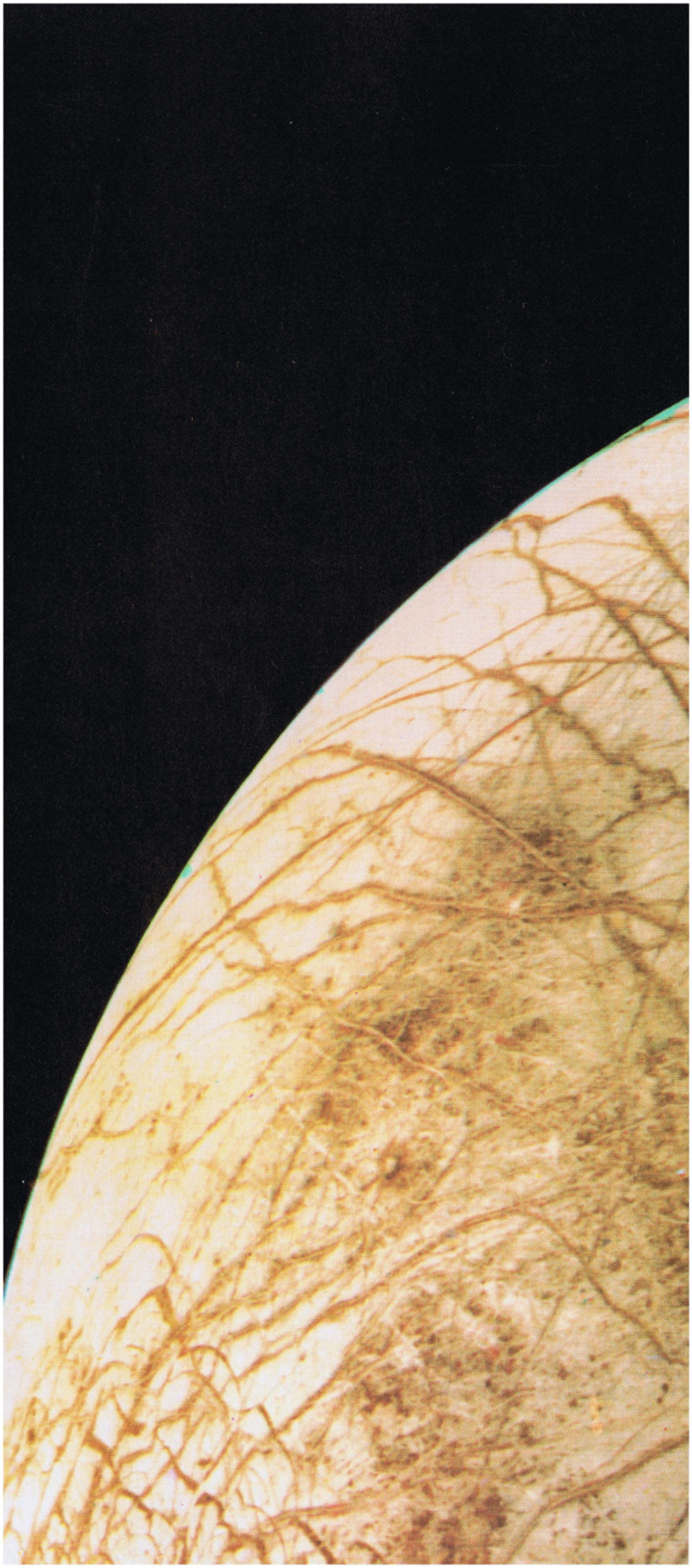


7/9/79 240,000 km (150,000 mi)

Europa's surface is probably a thin ice crust overlying water or softer ice (slush) about 100 kilometers (60 miles) thick that covers a silicate interior. The tectonic processes on Europa's surface create patterns that are drastically different from the fault systems seen on Ganymede's surface, where pieces of the crust have moved relative to each other. On Europa, the crust evidently fractures, but the pieces remain roughly in their original position. This Voyager 2 picture is composed of three images.

◁ **Europa,** approximately the same size and density as our Moon, is the brightest Galilean satellite. The surface displays a complex array of streaks, indicating that the crust has been fractured. In contrast to its icy neighbors Ganymede and Callisto, Europa has very few impact craters. The relative absence of features and low topography indicate that the crust is young and probably warm a few kilometers below the surface. The warmth is probably due to a combination of radioactive and tidal heating. The tidal heating within Europa is estimated to be ten percent that of the stronger tidal heating effect within Io. The regions that appear blue in this Voyager 2 image are actually white.

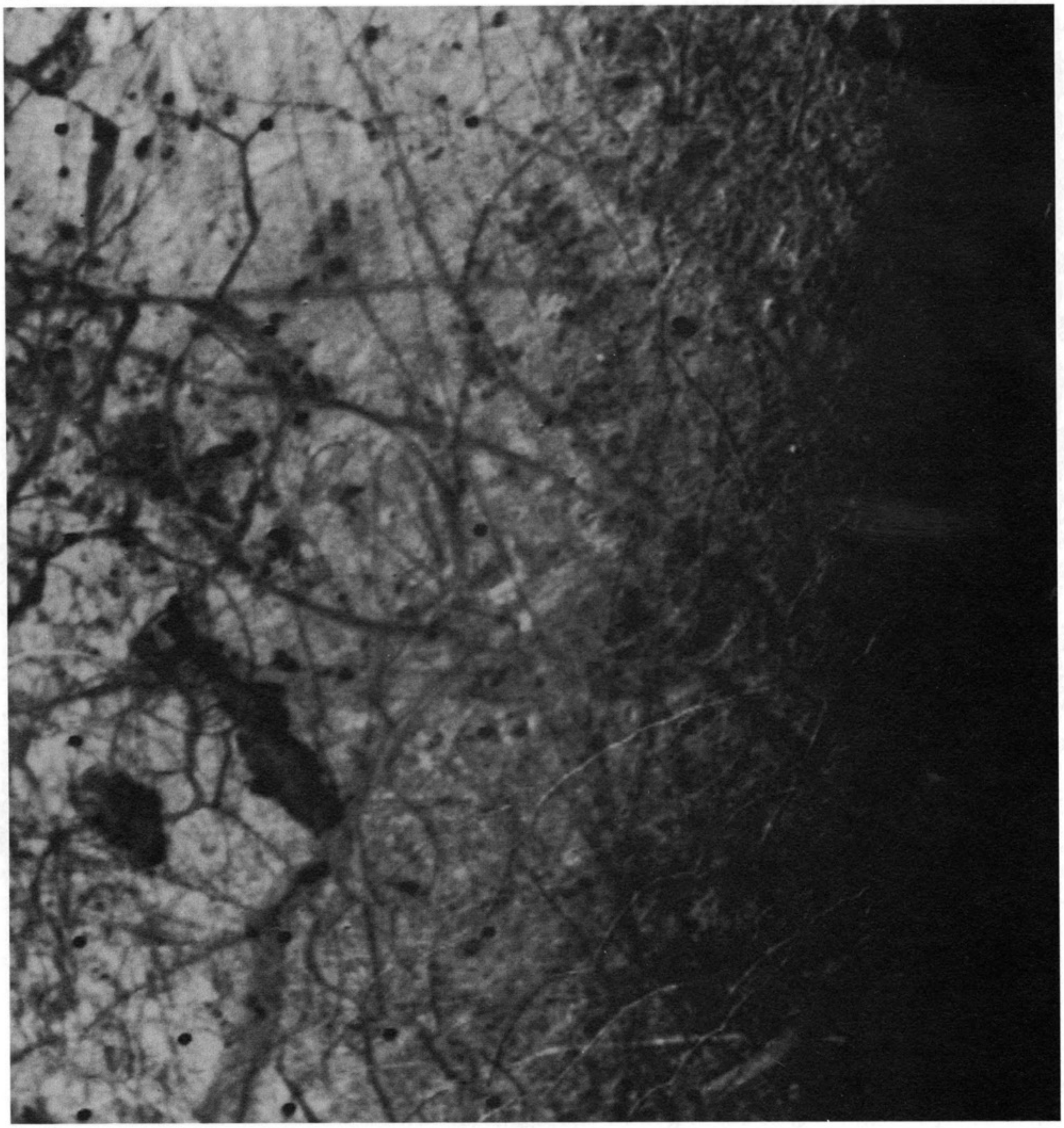
3/79 1.2 million km (750,000 mi)



7/9/79 240,000 km (150,000 mi)

Long linear fractures or faults which crisscross Europa's surface in various directions are over 1000 kilometers (600 miles) long in some places. Large fractures are 200 to 300 kilometers (125 to 185 miles) wide, wider than the crust is thick. Also visible are somewhat darker mottled regions that appear to have a slightly pitted appearance. No large craters (more than five kilometers in diameter) are identifiable in this Voyager 2 picture, indicating that this satellite has a very young surface relative to Ganymede and Callisto, although perhaps not as young as Io's surface. Scientists believe that the surface is a thin ice crust overlying water or softer ice and that the fracture systems are breaks in the crust. Resurfacing processes, such as the production of fresh ice or snow along the cracks and cold glacier-like flows, have probably removed evidence of impact events (cratering). Europa, therefore, appears to have many properties similar to Ganymede and Io.

7/9/79 240,000 km (150,000 mi)



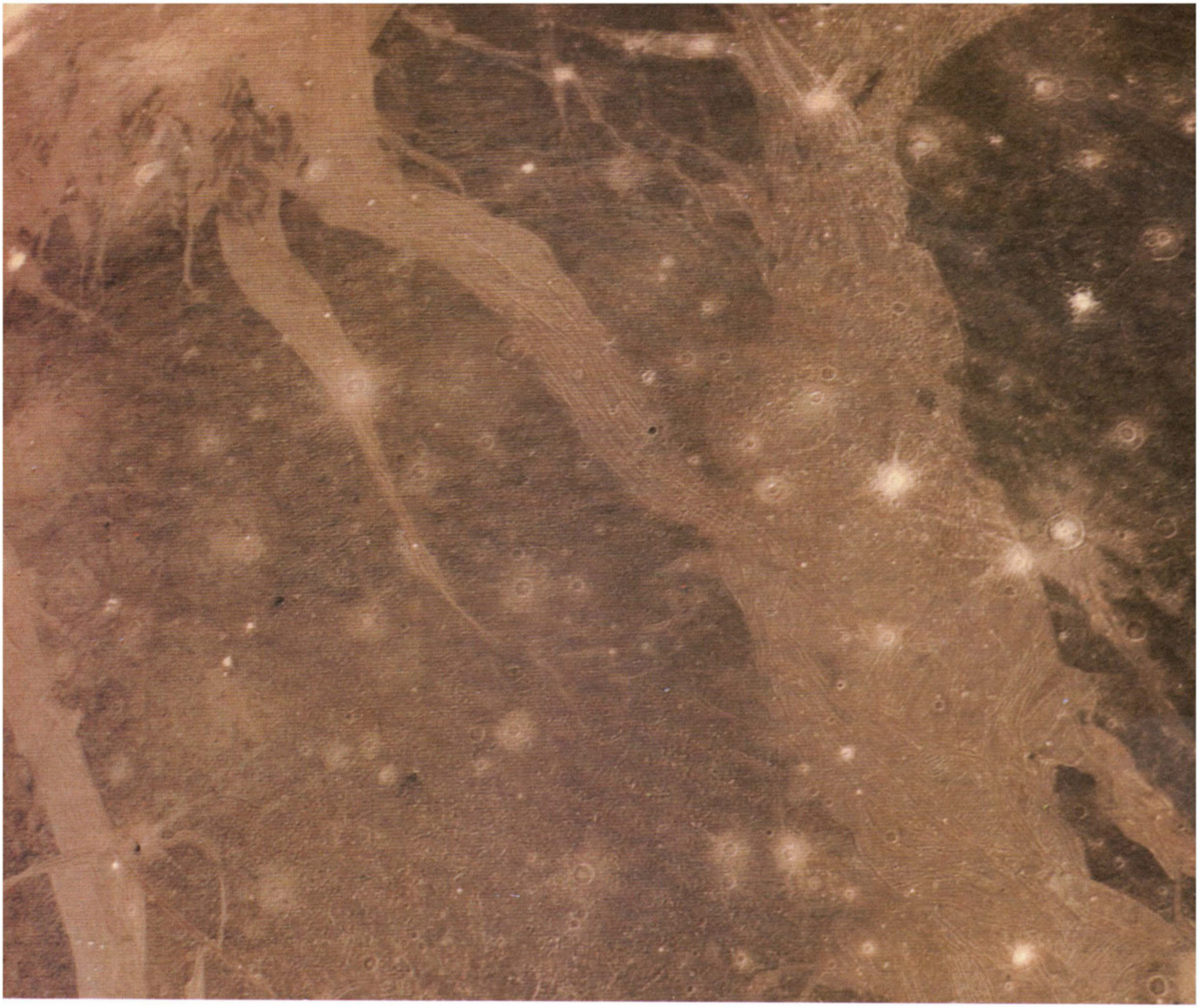
Complex narrow ridges, seen as curved bright streaks 5 to 10 kilometers (3 to 6 miles) wide and typically 100 kilometers (60 miles) long, characterize the surface topography of this view of Europa. The dark bands also visible in this Voyager 2 photo are 20 to 40 kilometers (12 to 25 miles) wide and up to thousands of kilometers long. The fractures on the icy surface are filled with material from beneath, probably as a result of internal tidal flexing which continually heats the thin outer ice crust. A few features are suggestive of degraded impact craters.

7/7/79 1.2 million km (750,000 mi)

The dark, cratered, circular feature in this Voyager 2 photograph is about 3200 kilometers (2000 miles) in diameter and is on the side of Ganymede opposite to that shown in the previous picture. This region is apparently the largest piece of ancient, heavily cratered crust left on Ganymede. The light branching bands are ridged and grooved terrain which are younger than the more heavily cratered dark regions. Despite the dramatic surface appearance, Ganymede is relatively devoid of topographic relief due to the consequences of glacier-like "creep" in the icy crust.

◁**Ganymede,** Jupiter's largest satellite, is about one and one-half times the size of our Moon but only about half as dense and is composed of about 50 percent water or ice and the rest rock. The bright surface of Ganymede is a complex montage of ancient, relatively dark and cratered terrain, grooved terrain that resulted from a dramatic history of tectonic movement in the icy crust, and bright young ray craters that expose fresh ice. This photograph was taken by Voyager 1.

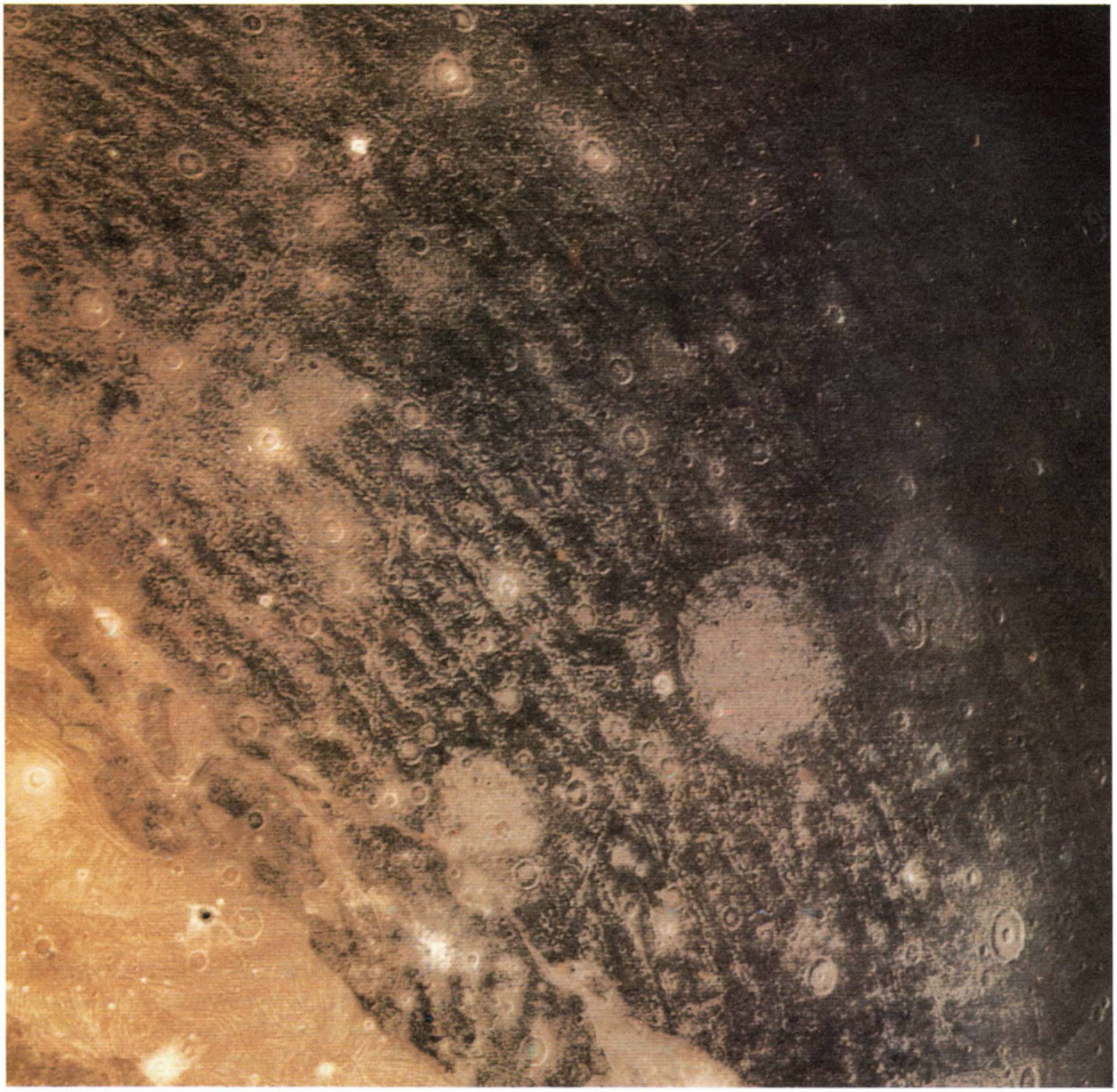
/4/79 2.6 million km (1.6 million mi)



7/8/79 312,000 km (194,000 mi)

Several different types of terrain common to Ganymede's surface are visible in this Voyager 2 picture. The boundary of the largest region of dark ancient terrain (also shown in the previous photo) can be seen to the right, revealing the light linear features that may be the remains of shock rings from an ancient impact. The broad light regions are the typical grooved structures contained within the light regions on Ganymede. On the lower left is another example of what might be evidence of large-scale lateral faulting in the crust; the band appears to be offset by a linear feature perpendicular to it. These are the first clear examples of lateral faulting seen on any planet other than Earth.

7/8/79 313,000 km (194,500 mi)



This color reconstruction of part of Ganymede's northern hemisphere, taken by Voyager 2, encompasses an area about 1300 kilometers (800 miles) across. It shows part of a dark, densely cratered region that contains numerous craters, many with central peaks. The large bright circular features have little relief and are probably the remnants of old, large craters that have been annealed by the flow of icy material near the surface. The gradually curving lines that press through the dark region suggest the presence of a large impact basin to the southwest, which has been obliterated by the subsequent formation of younger grooved terrain.

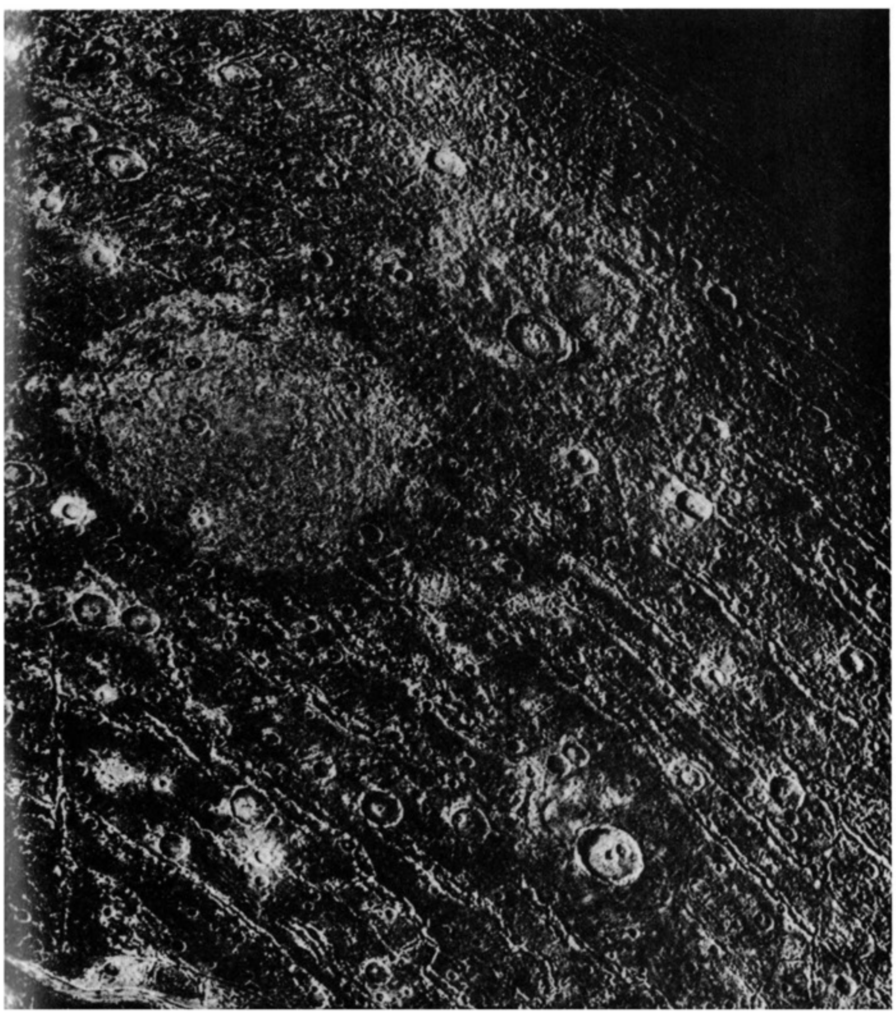
3/5/79 165,000 km (103,000 mi)

A broad, north–south strip of grooved terrain on Ganymede, offset by a traversing fault in the upper part of the picture, is shown in this Voyager 1 photograph. There are several other perpendicular fault lines farther down on the fault. Within the major light stripes, the more closely spaced, shallow grooves run parallel to the boundaries of the stripes. The larger striped features divide the cratered terrain into isolated polygons several hundred to about 1000 kilometers (600 miles) across.

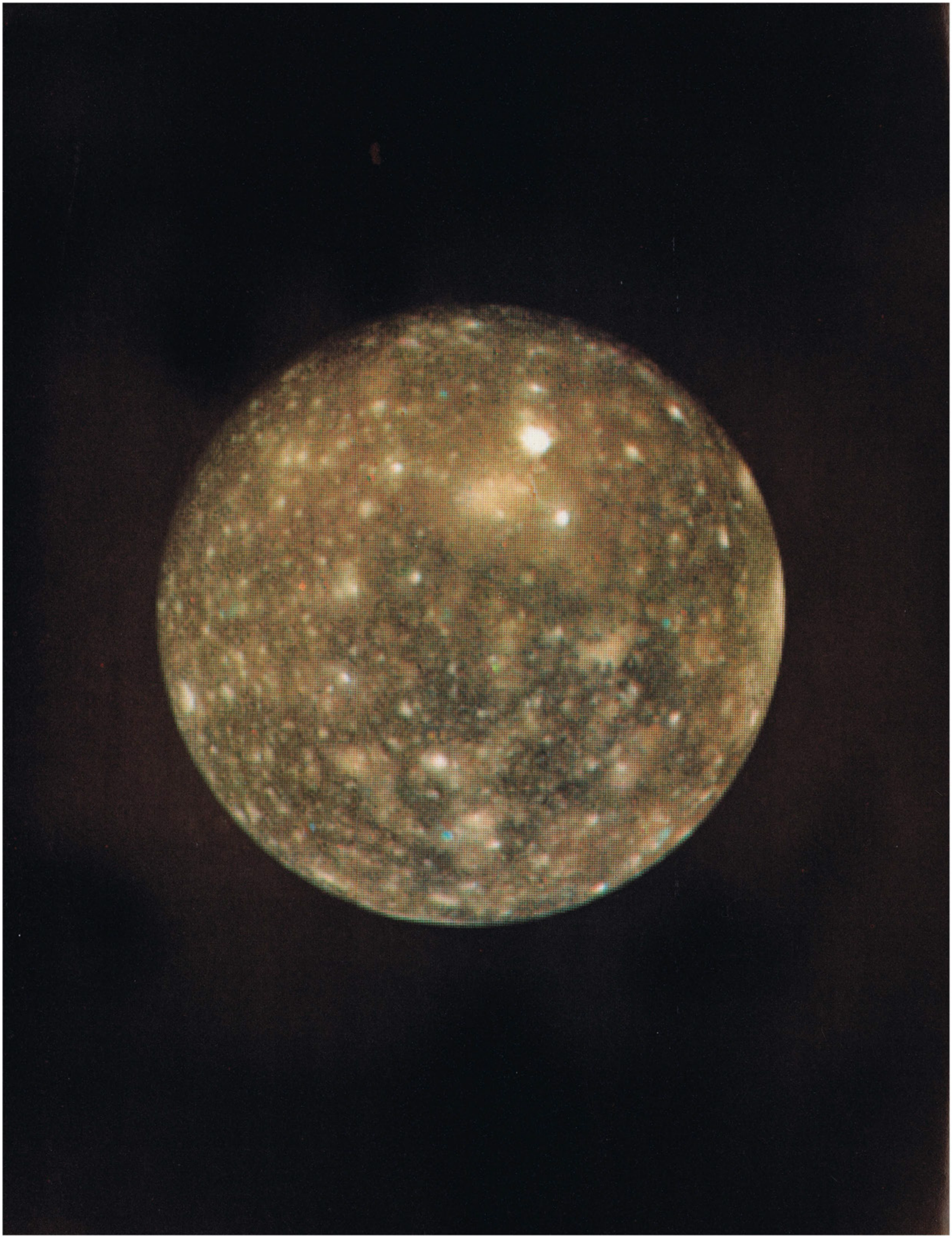
3/5/79 145,000 km (90,000 mi)

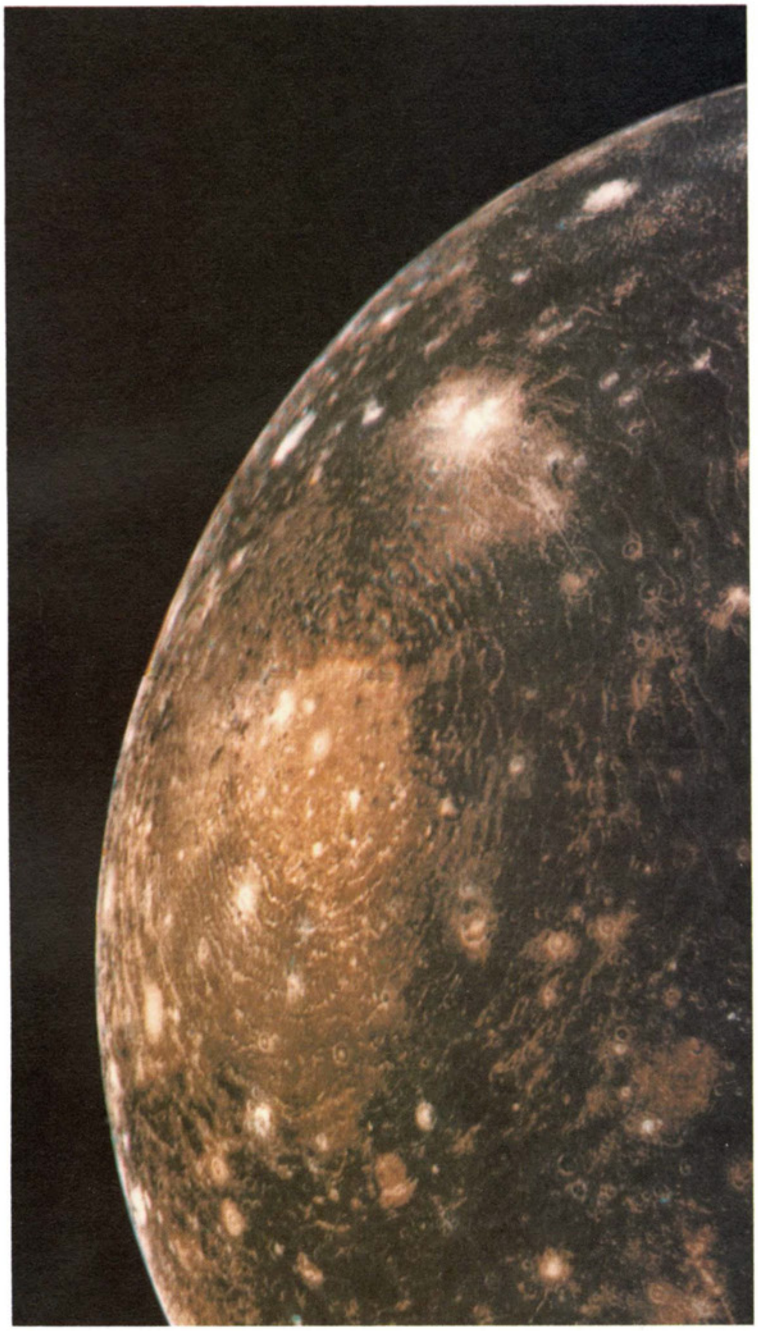
The grooved terrain at higher resolution emphasizes numerous interwoven linear features in this Voyager 1 picture, near the terminator on Ganymede. This suggests an early period in Ganymede's history when the crust was active and mobile, resembling Earth's plate tectonics in some ways. The causes of the extreme differences in crustal evolution between Callisto and Ganymede are under investigation. Combinations of radioactive heating and a greater degree of tidal heating for Ganymede are possibilities.

This mosaic of Ganymede, composed of photographs taken by Voyager 2, shows numerous impact craters, many with bright ray systems. The rough terrain at the lower right is the outer portion of a large, fresh impact basin that postdates most of the other terrain. The dark patches of heavily cratered terrain (right center) are probably ancient mixtures of ice and rock formed prior to the grooved terrain. The large rayed crater at the upper center is about 150 kilometers (95 miles) in diameter.



Curved troughs and ridges in this high-resolution Voyager 2 photograph of Ganymede are the distinctive characteristics of an enormous, ancient impact basin. The basin itself has been eroded by later geologic processes; only the shock ring features are preserved on the ancient surface. Near the bottom of the picture these curved markings are perforated with the younger, grooved terrain.



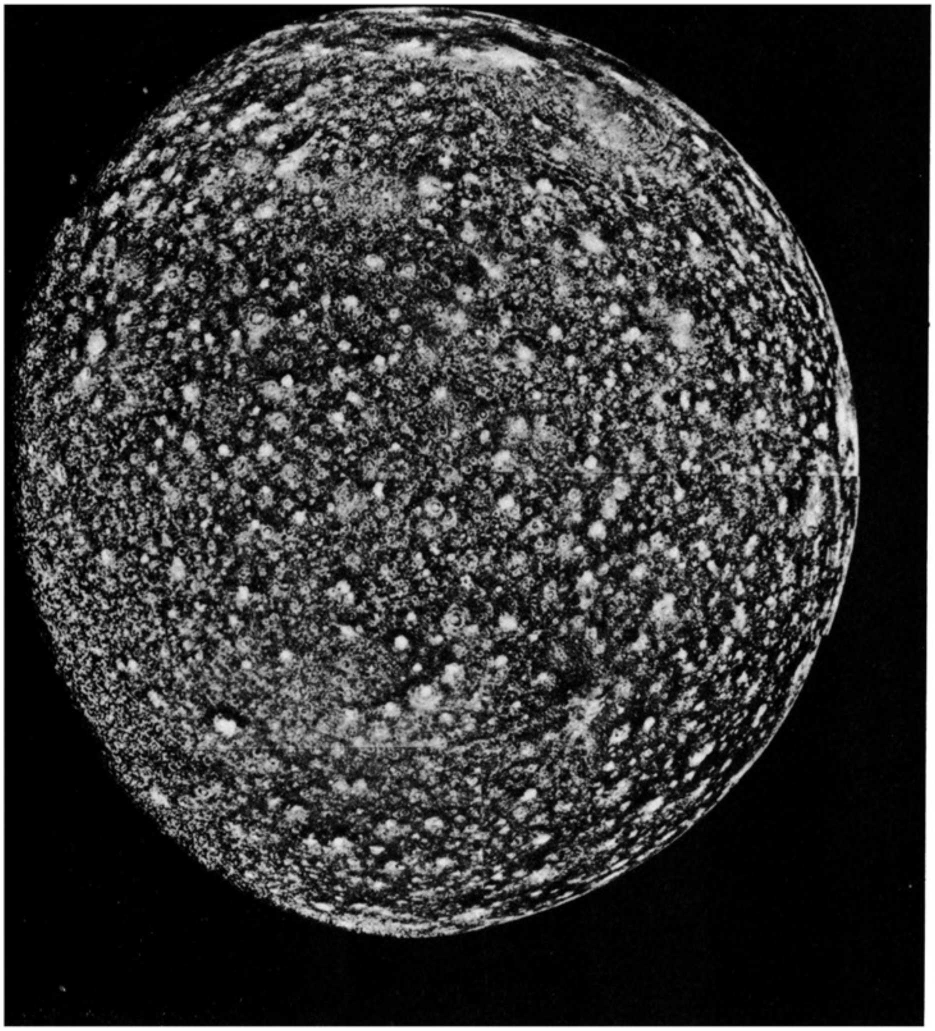


3/6/79 350,000 km (217,000 mi)

The prominent concentric ring structure shown in this Voyager 1 four-picture mosaic of Callisto is believed to be a large impact basin, similar to Mare Orientale on the Moon and Caloris Basin on Mercury. The bright circular spot is about 600 kilometers (360 miles) across, and the outer ring is about 2600 kilometers (1560 miles) across. This is the first recognized basin in the Jovian system and supports the assumption that Callisto's surface is old. The lack of high ridges, ring mountains, or a large central depression suggests that the impacting body caused melting, some flow, and shock waves, and that the refreezing occurred in time to preserve the concentric shock rings.

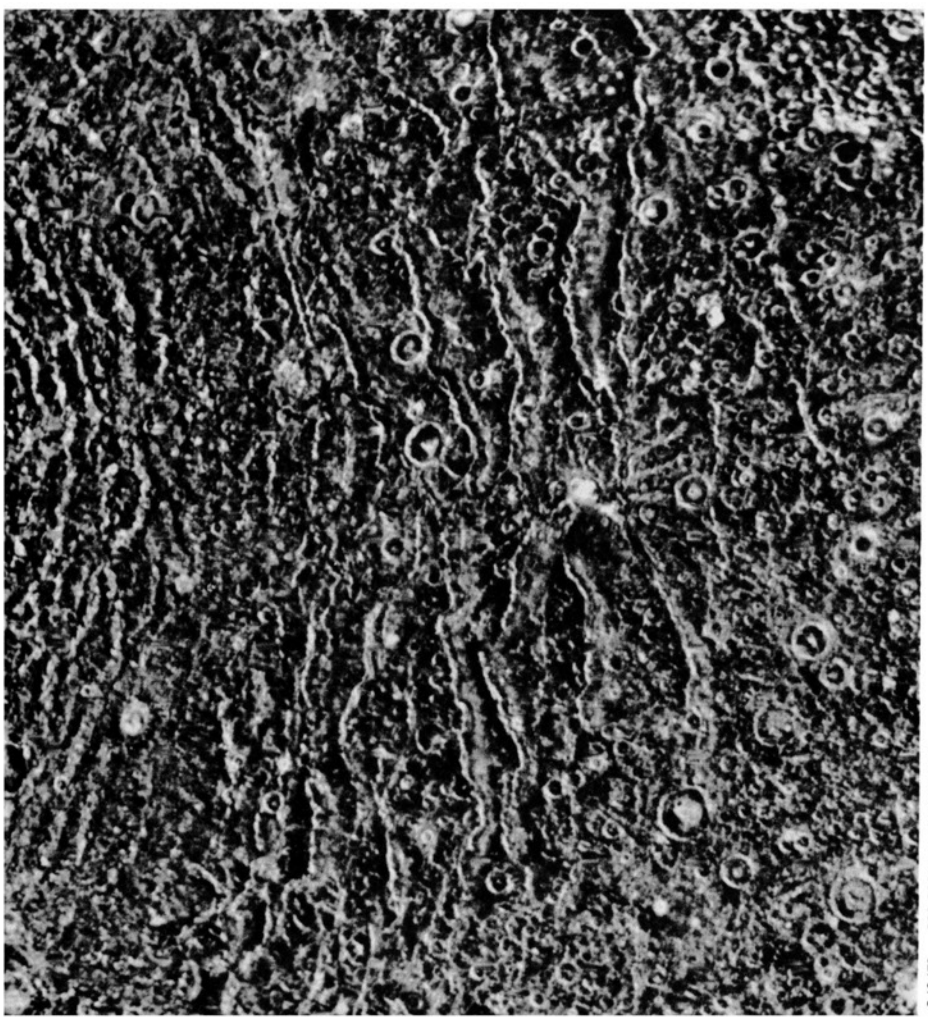
◁ **Callisto,** only slightly smaller than Ganymede, has the lowest density of all the Galilean satellites, implying that it has large amounts of water in its bulk composition. Its surface is darker than the other Galilean satellites, although it is still twice as bright as our Moon. This Voyager 2 image shows Callisto to have the most heavily cratered and, therefore, the oldest surface of the Galilean satellites, probably dating back to the period of heavy meteoritic bombardment ending about four billion years ago.

7/79 2.3 million km (1.4 million mi)



7/7/79 390,000 km (245,000 mi)

Callisto is the most heavily cratered planetary body in our solar system. In this Voyager 2 nine-frame mosaic, a special computer filter was used to provide high contrast in the surface topography. The impact structure visible at the upper right edge of the satellite is smaller than the largest one found by Voyager 1 but more detail is obvious; it is estimated that 15 concentric rings surround the bright center. Many hundreds of moderate-sized craters are also visible, a few with bright ray patterns. The limb is smooth, which is consistent with Callisto's icy composition.



3/6/79 200,000 km (125,000 mi)

This high-resolution image of Callisto, photographed by Voyager 1, shows details of the large ring structure surrounding the remains of the ancient impact basin visible on page 35. The surface area shown in this image is at the right edge and slightly above the center of the picture on page 35. The relatively undisturbed region on the right shows the shoulder-to-shoulder large impact craters typical of most of Callisto's surface. A decrease in crater density toward the center of the structure (to the left) is evident, and is caused by the destruction of very old craters by the large impact that formed the ring structure.

The Voyager Mission

The Voyager mission is focused on the exploration of the Jupiter and Saturn systems. The alignment of these large planets permits the use of a gravity-assist trajectory in which the gravity field of Jupiter and Jupiter's motion through space may be used to hurl the spacecraft on to Saturn. In 1977, a rare alignment (once every 176 years) of our four outer planets—Jupiter, Saturn, Uranus, and Neptune—may permit a gravity-assist trajectory to Uranus and even to Neptune for Voyager 2.

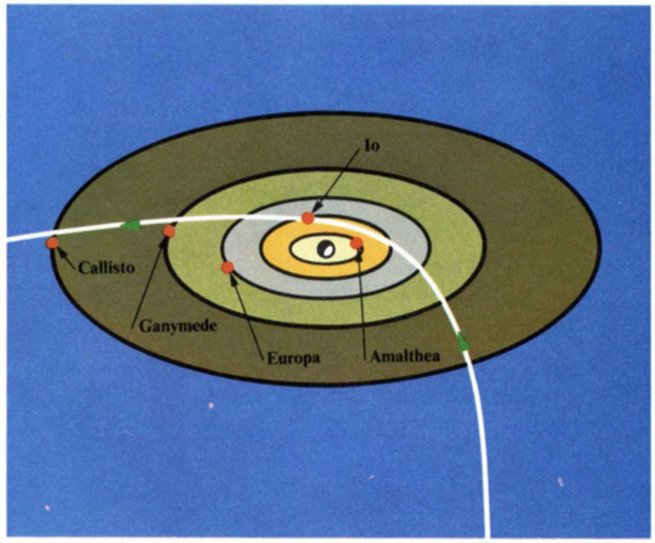
Voyagers 1 and 2 began their journeys in the late summer of 1977, catapulted into space by a Titan/ Centaur launch vehicle from Cape Canaveral, Florida. With them went the hopes and dreams of thousands of people who had worked to create them and their mission.

The Voyager spacecraft are unique in many respects. Since their journeys are taking them far from the Sun, the Voyagers are nuclear powered rather than solar powered. The Voyagers are the fastest man-made objects ever to have left Earth. In fewer than ten hours, they had crossed the Moon's orbit. This compares to about three days for an Apollo flight and one day for the Mariner and Viking spacecraft. Their launches marked the end of an era in space travel—the end of the planned use of Titan/ Centaur launch vehicles. With the advent of the Space Shuttle in the 1980s, future spacecraft will be launched from the Shuttle Orbiter.

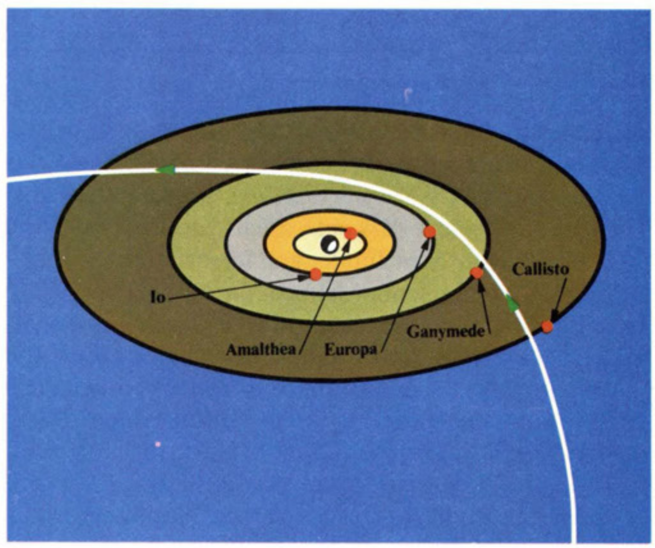
Voyager 1 was launched 16 days after its sister ship, but because of a different trajectory, it arrived at Jupiter four months ahead of Voyager 2. Both spacecraft spent more than nine months crossing the asteroid belt, a vast ring of space debris circling the Sun between the orbits of Mars and Jupiter. During their 16- and 20-month journeys to Jupiter, the spacecraft tested and calibrated all of their instruments, exercised their scan platforms, and measured particles and fields in interplanetary space. As the spacecraft neared the planet, the cameras showed the dramatic visible changes that had taken place in the five years since Jupiter had been photographed by Pioneer 11. And for the first time, we got a close look at some of Jupiter's moons: Amalthea, Io, Europa, Ganymede, and Callisto.

Targeted for the closest look at Io, Voyager 1 flew the more hazardous course, passing between Jupiter and Io, where the radiation environment is the most intense. Voyager 2's flight path gave Jupiter and its intense radiation a much wider berth. Unlike Voyager 1, which encountered the five innermost satellites as it was leaving Jupiter, Voyager 2 encountered the satellites as it was approaching the planet, thus providing closeup photography of opposite sides of the satellites.

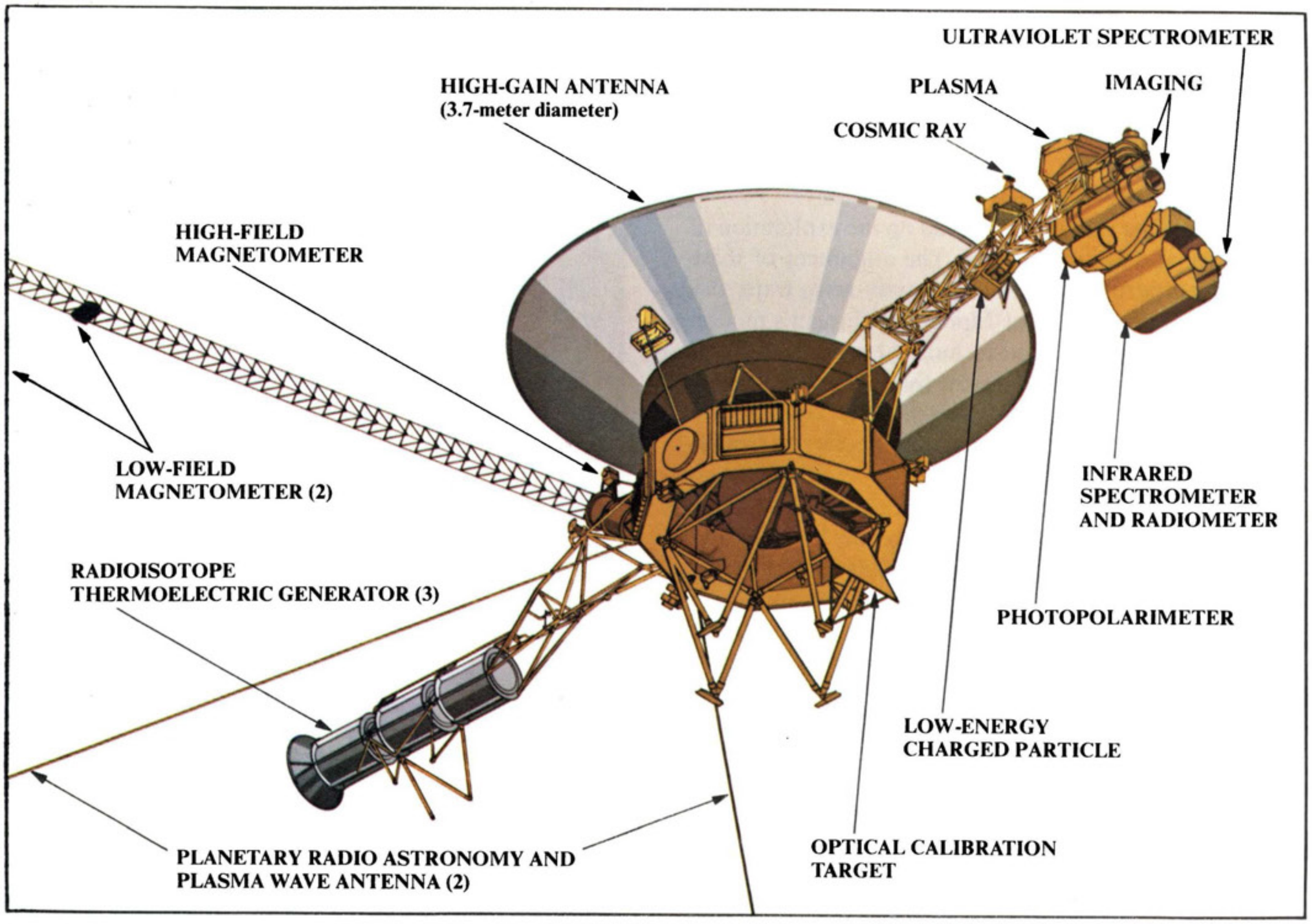
Arriving at Jupiter from slightly different angles, both spacecraft measured the large, doughnut-shaped ring of charged sulfur and oxygen ions, called a torus, encircling



March 5, 1979. *Voyager 1's unique flight path allowed scientists to study at close range 5 of Jupiter's 13 known satellites. Each is shown at its closest point to the trajectory of Voyager 1's outbound flight away from Jupiter. Closest approach was 280,000 kilometers (174,000 miles) from Jupiter.*



July 9, 1979. *Voyager 2's closest approach to Jupiter was 645,000 kilometers (400,000 miles) from the planet. Voyager 2 encountered the satellites on its inbound journey to Jupiter, which enabled the spacecraft to photograph the opposite sides of the satellites.*



Voyager spacecraft and scientific instruments.

the planet at about the orbit of Io. Then, both spacecraft disappeared behind Jupiter, out of view of Earth and Sun, for about two hours. During this time, measurements were taken on the planet's dark side. Each spacecraft took over 15,000 photographs of Jupiter and its satellites.

From the moment of launch, the Voyager spacecraft have been monitored by a worldwide tracking system of nine giant antennas strategically located around the world in California, Spain, and Australia to ensure constant radio contact with the spacecraft as the Earth rotates. Radio contact with Voyagers 1 and 2 has not been instantaneous, however. When Voyager 1 flew past Jupiter, radio signals between Earth and the spacecraft took 37 minutes; when Voyager 2 arrived, the signals took 52 minutes because by then the planet was farther from Earth.

The pictures in this book were taken by a shuttered television-type camera. Each picture is composed of 640,000 dots, which were converted into binary numbers before being radioed to Earth. When the signals reached Earth, they were reconverted by computer into dots and reassembled into the original image. Most of the color pictures are composed of three images, each one taken through a different color filter: blue, orange, or green. The images were combined and the original color was reconstructed by computer. The computer eliminated many of the imperfections that crept into the images, and enhanced some of the images by emphasizing different colors.

Designed to provide a broad spectrum of scientific investigations at Jupiter, the science instruments investigated atmospheres, satellites, and magnetospheres. The scientific investigations for the Voyager mission and their Jovian encounter objectives are shown in the table on page 40.

After their closest approaches to Jupiter, both spacecraft fired their thrusters, retargeting for their next goal, the Saturn system. Scientists will still be studying the wealth of new information about Jupiter when Voyager 1 reaches Saturn in November 1980, and Voyager 2 follows in August 1981. After Voyager 1 encounters Saturn, Voyager 2 may be retargeted to fly past Uranus in 1986. Upon completion of their planetary missions, both spacecraft will search for the outer limit of the solar wind, that boundary somewhere in our part of the Milky Way where the influence of the Sun gives way to other stars of the galaxy. Voyagers 1 and 2 will continue to study interstellar space until the spacecraft signals can no longer be received.

Scientific Highlights

Some of the most important information gathered by Voyagers 1 and 2 on the Jovian system is presented pictorially in this book and is supplemented here with brief summaries of the major discoveries, observations, and theories.

Jupiter

The atmosphere of Jupiter is colorful, with cloud bands of alternating colors. A major characteristic of the atmosphere is the appearance of regularly spaced features. Around the northern edge of the equator, a train of plumes is observed, which has bright centers representative of cumulus convection similar to that seen on Earth. At both northern and southern latitudes, cloud spots are observed spaced almost all the way around the planet, suggestive of wave interactions. The cloud structures in the northern and southern hemispheres are distinctly different. However, the velocities between the bright zones and dark belts appear to be symmetric about the equator, and stable over many decades. This suggests that such long-lived and stable features may be controlled by the atmosphere far beneath the visible clouds. The Great Red Spot possesses the same meteorological properties of internal structure and counterclockwise rotation as the smaller white spots. The color of the Great Red Spot may indicate that it extends deep into the Jovian atmosphere. Cloud-top lightning bolts, similar to those on Earth, have also been found in the Jovian atmosphere. At the polar regions, auroras have been observed. A very thin ring of material less than one kilometer (0.6 mile) in thickness and about 6000 kilometers (4000 miles) in radial extent has been observed circling the planet about 55,000 kilometers (35,000 miles) above the cloud tops.

Amalthea

Amalthea is an elongated, irregularly shaped satellite of reddish color. It is 265 kilometers (165 miles) long and 150 kilometers (90 miles) wide. Just like the large Galilean satellites, Amalthea is in synchronous rotation, with its long axis always oriented toward Jupiter. At least one significant color variation has been detected on its surface.

Io

Eight active volcanoes have been detected on Io, with some plumes extending up to 320 kilometers (200 miles) above the surface. Over the four-month interval between the Voyager 1 and 2 encounters, the active volcanism appears to have continued. Seven of the volcanoes were photographed by Voyager 2, and six were still erupting.

The relative smoothness of Io's surface and its volcanic activity suggest that it has the youngest surface of Jupiter's moons. Its surface is composed of large amounts of sulfur and sulfur dioxide frost, which account for the primarily yellow-orange surface color. The volcanoes seem to eject a sufficient amount of sulfur dioxide to form a doughnut-shaped ring (torus) of ionized sulfur and oxygen atoms around Jupiter near Io's orbit. The Jovian magnetic field lines that go through the torus allow particles to precipitate into the polar regions of Jupiter, resulting in intense ultraviolet and visible auroras.

Europa

Europa, the brightest of Jupiter's Galilean satellites, may have a surface of thin ice crust overlying water or softer ice, with large-scale fracture and ridge systems appearing in the crust. Europa has a density about three times that of water, suggesting it is a mixture of silicate rock and some water. Very few impact craters are visible on the surface, implying a continual resurfacing process, perhaps by the production of fresh ice or snow along cracks and cold glacier-like flows.

Ganymede

Ganymede, largest of Jupiter's 13 satellites, has bright "young" ray craters; light, linear stripes resembling the outer rings of a very large, ancient impact basin; grooved terrain with many faults; and regions of dark, heavily cratered terrain. Among the Galilean satellites, Ganymede probably has the greatest variety of geologic processes recorded on its surface and may be the best example for studying the evolution of Jupiter's inner satellites. Imbedded within Jupiter's magnetosphere, Ganymede is subjected to the influences of the corotating charged-particle plasma and an interaction may exist with this plasma. No atmosphere has been detected.

Callisto

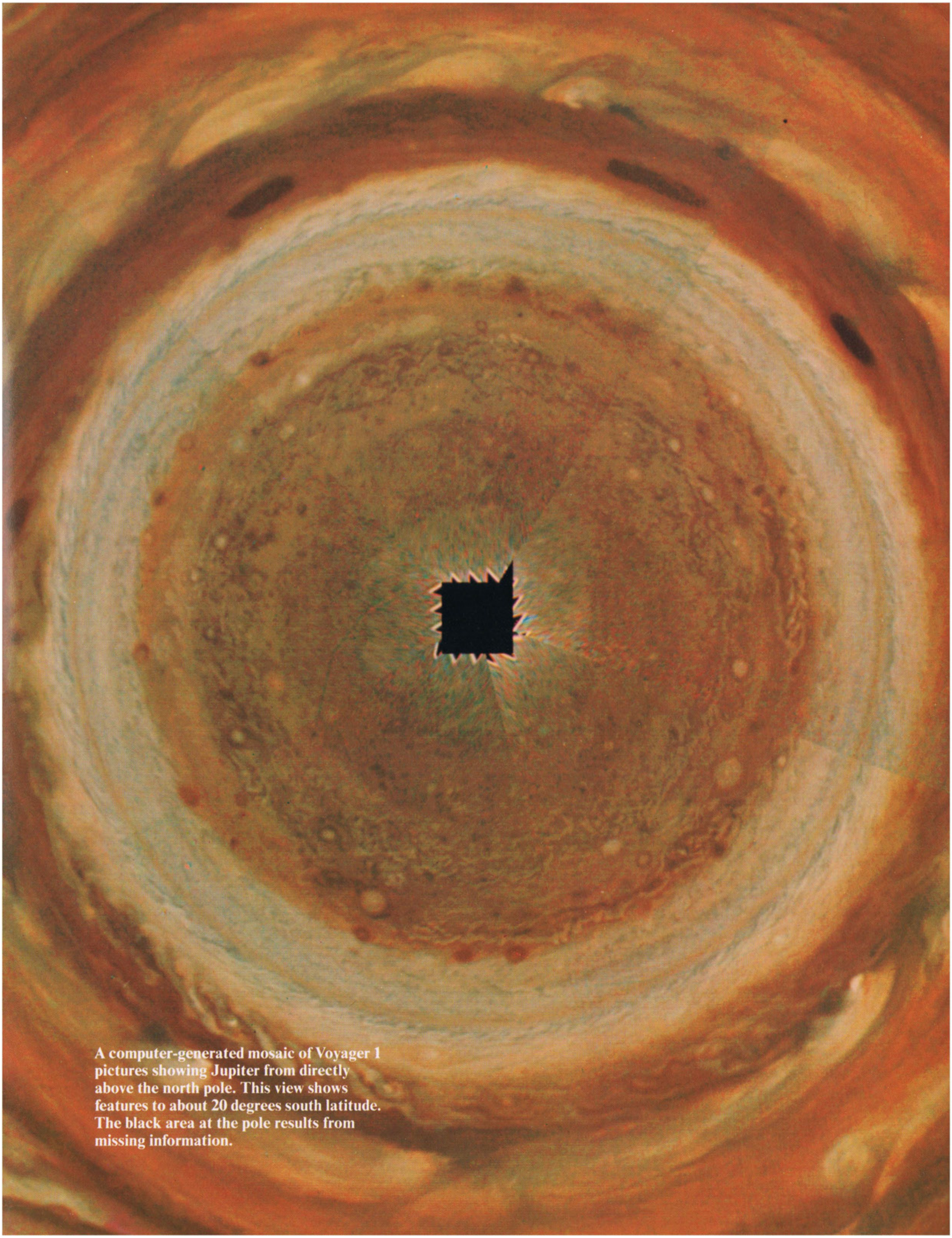
The icy, dirt-laden surface of Callisto appears to be very ancient and heavily cratered. The large concentric rings indicate the remains of several enormous impact basins, created by huge meteors crashing into the surface, and since erased by the flow of the crust. Callisto's density (less than twice that of water) is very close to that of Ganymede, yet there is little or no evidence of the crustal motion and internal activity that is visible on Ganymede.

The Magnetosphere

Perhaps the largest structure in the solar system is the magnetosphere of Jupiter. This is the region of space which is filled with Jupiter's magnetic field and is bounded by the interaction of that magnetic field with the solar wind, which is the Sun's outward flow of charged particles. The plasma of electrically charged particles that exists in the magnetosphere is flattened into a large disk more than 4.8 million kilometers (3 million miles) in diameter, is coupled to the magnetic field, and rotates around Jupiter. The Galilean satellites are located in the inner regions of the magnetosphere where they are subjected to intense radiation bombardment. It appears that Io is a source of the sulfur and oxygen ions which fill the magnetosphere. Another magnetospheric interaction is the electrical connection between Io and Jupiter along the magnetic field lines that leave Jupiter and intersect Io. This magnetic flux tube was examined by Voyager 1 and a flow of about five million amperes of current was measured, which was considerably more than anticipated. Voyager also discovered a new low-frequency radio emission coming from Jupiter, which is possibly associated with the Io torus.

Scientific investigations of the Voyager mission

Investigation	Typical Jovian encounter objectives
Imaging science	High-resolution reconnaissance over large phase angles; atmospheric dynamics; geologic structure of satellites
Infrared radiation	Atmospheric composition, thermal structure and dynamics; satellite surface composition and thermal properties
Photopolarimetry	Atmospheric aerosols; satellite surface texture and sodium cloud
Radio science	Atmospheric and ionospheric structure, constituents, and dynamics
Ultraviolet spectroscopy	Upper atmospheric composition and structure; auroral processes; distribution of ions and neutral atoms in the Jovian system
Magnetic fields	Planetary magnetic field; magnetospheric structure; Io flux tube currents
Plasma particles	Magnetospheric ion and electron distribution; solar wind interaction with Jupiter; ions from satellites
Plasma waves	Plasma electron densities; wave–particle interactions; low-frequency wave emissions
Planetary radio astronomy	Polarization and spectra of radio frequency emissions; Io radio modulation process; plasma densities
Low-energy charged particles	Distribution, composition, and flow of energetic ions and electrons; satellite–energetic particle interactions
Cosmic ray particles	Distribution, composition, and flow of high-energy trapped nuclei; energetic electron spectra



A computer-generated mosaic of Voyager 1 pictures showing Jupiter from directly above the north pole. This view shows features to about 20 degrees south latitude. The black area at the pole results from missing information.

National Aeronautics and
Space Administration

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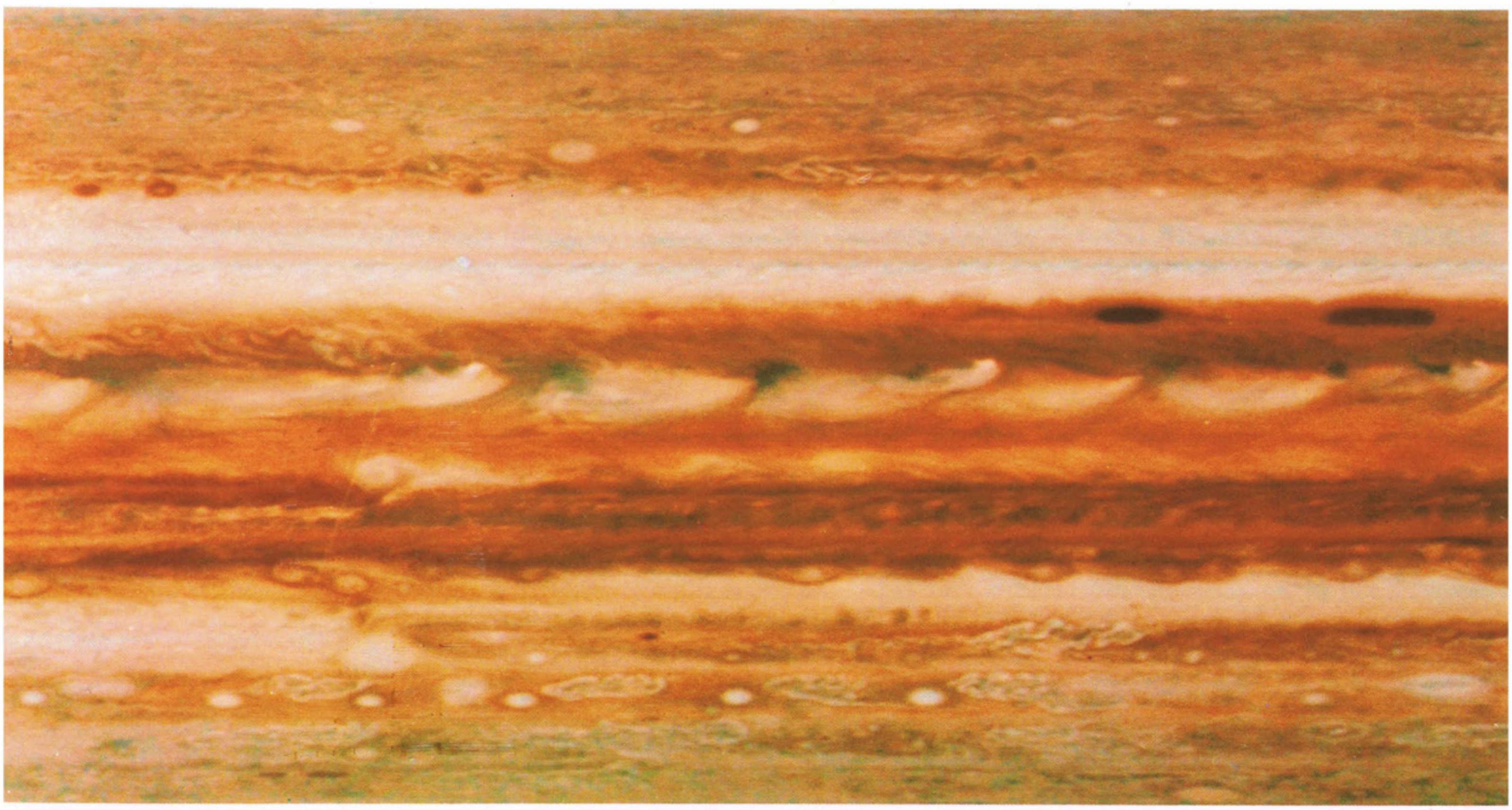
California Institute of Technology
Pasadena, California



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