

A dramatic view of three of the five new worlds encountered by Voyager 1 at Jupiter. Silhouetted against the giant planet are two of its satellites, Io (220,000 miles above the Great Red Spot) and to the right Europa (375,000 miles above the clouds). The two satellites are about the same size but of very different appearance and history.

Voyager 1 at Jupiter

An Encounter with Five New Worlds

by Edward C. Stone

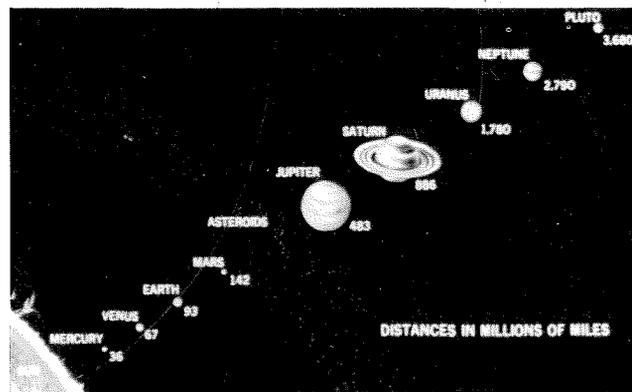
Voyager 1 at Jupiter

In January, February, and March 1610, Galileo first turned his newly developed, eight-power telescope toward the celestial sphere, discovering that four smaller bodies were orbiting Jupiter and providing him with his first direct evidence supporting the Copernican theory. Those four Jovian satellites are now called the Galilean satellites. Three hundred and sixty-nine years later, also in January, February, and March, Voyager 1 carried a complex array of sensors past Jupiter and the Galilean satellites, producing results that are in many ways as surprising as Galileo's discovery.

The Voyager 1 observations are, of course, the result of the combined efforts of many individuals over a number of years. Engineers and scientists at Caltech's Jet Propulsion Laboratory have the responsibility for conducting the Voyager Project for NASA. In addition, more than 100 scientists from the United States and Europe are associated with the 11 scientific investigations selected by NASA in 1972. (One of those investigations is headed by R. E. Vogt, chairman of the Division of Physics, Mathematics and Astronomy.) Although the 11 investigations use separate instruments to measure quite diverse phenomena, the resulting studies can nevertheless be assigned to three general areas: studies of the atmosphere, of the magnetosphere, and of the satellites of Jupiter.

In the first of these areas are studies of the composition and the dynamics (or weather) of the Jovian atmosphere. There is interest in the composition of the planet because it is thought that Jupiter has managed to retain a more representative sample of the material out of which the solar system was made than has the Earth. Since Jupiter is five times as far from the Sun as the Earth, it retained amounts of the lighter elements such as hydrogen and helium that are more nearly proportional to the amounts present when the planets and the Sun formed some four and one-half billion years ago. The more volatile materials are missing from the inner planets of our solar system — Mercury, Venus, Earth, and Mars — resulting in rather small rocky bodies, while the outer planets — Jupiter, Saturn, Uranus, and Neptune — which formed far from the heat of the Sun, more closely resemble it. Thus Jupiter is a massive sphere of gas, possibly with a small, molten rock core. As a result, there is no solid surface to Jupiter, and what is seen in the images of Jupiter are cloud layers at the top of a very deep atmosphere.

The banded appearance of the Jovian clouds is a clear indication that the Jovian weather patterns are different from Earth's. Obviously, the same basic processes are involved, but the factors that control those processes are present in different proportions. By studying how those



The planets of the solar system, ranked in order of distance from the Sun and drawn to scale in size. The largest, Jupiter, is five times as far from the Sun as Earth, eleven times as large as Earth, and a sphere of gas instead of a ball of rock.

different proportions alter the weather patterns, we expect to better identify which are the most important factors and to improve our understanding of the basic processes.

One example of an important difference between Jupiter and Earth is the source of heat for the polar regions. Jupiter, unlike Earth, has a significant internal heat source, evidently because it is still cooling off from the heat generated during the gravitational-contraction phase of its formation. The net result is that the heat coming from the inside of Jupiter is about equal to the amount of heat it receives from the Sun. This internal heat source may thus provide heat to the polar regions without requiring the transport of solar energy from the equator as must happen on Earth. This could be an important factor in the formation of the uninterrupted horizontal banded pattern of clouds that is evident in photographs.

Another important factor is that Jupiter lacks a solid surface so that large differences in pressure can't be maintained deep in the atmosphere. The fact that Jupiter has a 10-hour rotation period and a very large radius means that it has very high surface velocity (approximately 28,000 mph), and this too changes the proportion of the factors that go to make up the Jovian weather system.

From ground-based observations it was known that the broad regions of clouds on Jupiter possessed a somewhat regular pattern of eastward and westward winds. Voyager, however, discovered an unexpected prevalence of vortical or rotational motion. In both the northern and southern hemispheres there are numerous small high-pressure regions or spots ("small" on the Jovian scale means something like half the size of Earth) that rotate rapidly — clockwise in the northern hemisphere and counterclockwise in the southern. The spots in the northern hemisphere,

which are a brownish color, occasionally collide, rotating about each other in a clockwise motion.

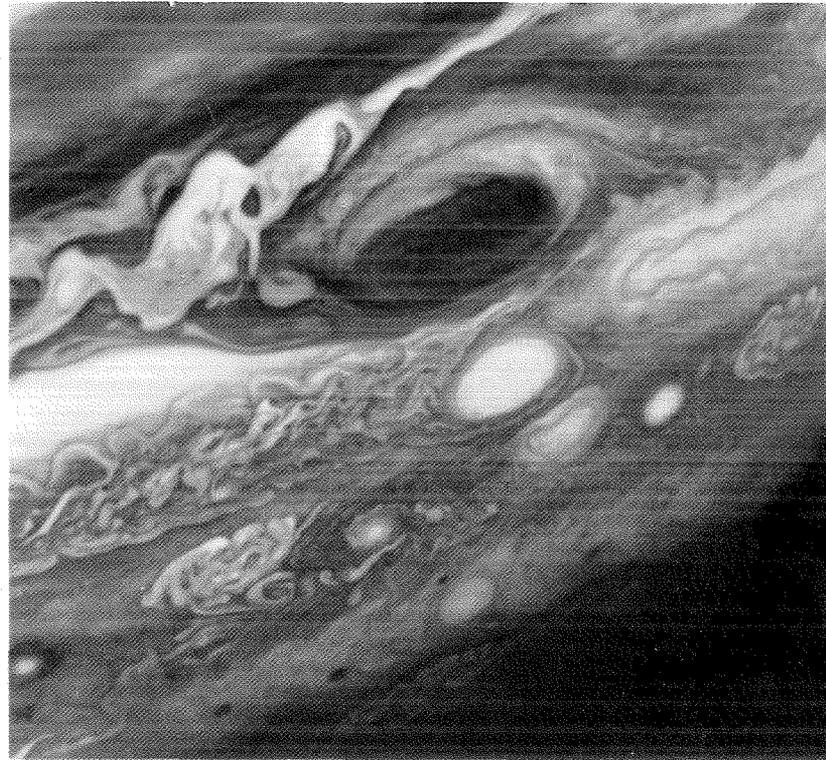
The Great Red Spot is the most obvious vortex in the southern hemisphere and flows counterclockwise. But there are also three white ovals and other white cloud structures that are regularly spaced around the planet at latitudes just south of the Great Red Spot and that also rotate in a counterclockwise direction. All of these have great dynamical stability. The Great Red Spot was first observed more than 300 years ago, and the formation of the white ovals out of the collapse of a zone of clouds was observed about 40 years ago.

The source of energy that drives these rotational flows is unknown. One possibility is that they are driven by an upwelling of gaseous material in the center of a spot. The material condenses as it reaches the top of the cloud deck and in the process releases heat. Or just the reverse could occur. Energy could be fed into the spots by the east-west winds that blow past them. Very careful measurements of the rotational flows may indicate whether the material is diverging (spiraling outward with latent heat from the condensation) or converging (spiraling inward because energy is being fed in by the zonal winds).

There are also a number of discrete white cloud structures that encounter the Great Red Spot as they circulate about the planet. Even though the shapes of the individual structures are severely distorted as they circle around the Great Red Spot, they nevertheless maintain their individual integrity, sometimes circling a second time, and then breaking away and continuing on around the planet. Simple, unstructured clouds would be unable to maintain such integrity. A study of the interaction of these objects may provide important clues to the dynamics of the Jovian atmosphere.

Since pressure differences in the upper atmosphere drive the winds, another important tool in the study of the weather on Jupiter is the measurement of temperature as a function of depth or pressure. The temperature and pressure of the atmosphere decrease with increasing distance from the center of the planet where the temperature is tens of thousands of degrees. The temperature at the level of the visible clouds, which are condensed ammonia, is only about 150°K, and at a level 40 km higher it drops to a minimum of about 110°K. At still higher altitudes, the temperature again rises partly because of solar heating. Water ice clouds, similar to those on Earth, form a layer well below the visible clouds where the temperature is near the freezing point of water (273°K) and the pressure is about five times that on the Earth's surface.

There are, of course, some trace chemicals among the

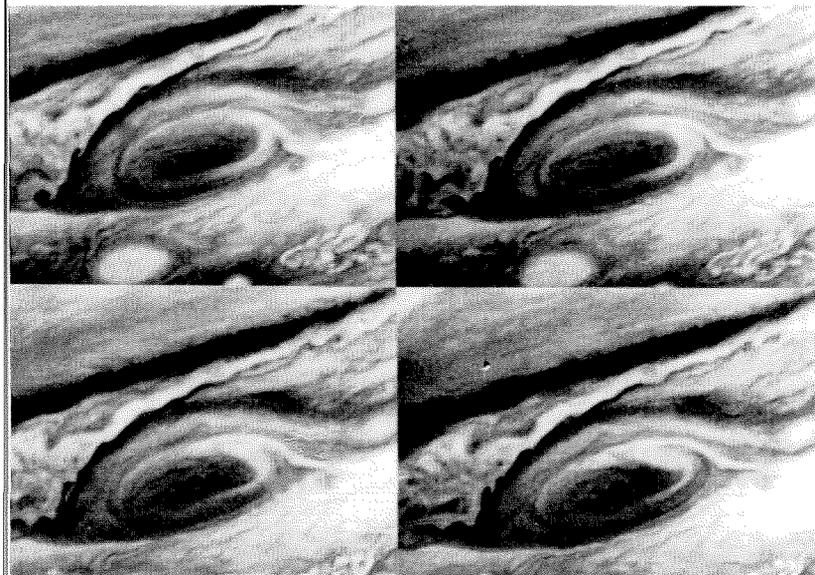


Almost a closeup of Jupiter's Great Red Spot, taken when Voyager 1 was 5.7 million miles from Jupiter. In addition to the complexity of the cloud patterns around and within it, the Great Red Spot offers other challenges to understanding. For example, in general the dark regions on Jupiter are warmer, but the Great Red Spot, dark as it is, is colder than neighboring areas. It is believed to soar about 15 miles above the surrounding clouds, and its length is about three times the diameter of Earth.

constituents of Jupiter, and they are almost surely the basis for the different cloud colors. Considering the pressures and temperatures that are also present, it seems likely those trace chemicals are rather complex molecules. The lightning activity that Voyager observed on Jupiter may have a significant role in the formation of at least some complex molecules.

A second area of study was that of the Jovian magnetosphere, that is, the magnetic field and trapped radiation environment surrounding Jupiter. The Jovian magnetic field is the largest structure in the solar system, extending more than two million miles from Jupiter. If you could see it from Earth, it would appear as large as the Sun even though it is five times as far away. Because of the great extent of the magnetic field, all of the major Jovian satellites are buried deep inside the magnetosphere. By comparison, Earth's Moon is safely outside of the region of intense magnetic field and radiation. The satellite Io, however, acts as a conductor moving in Jupiter's magnetic field, and some 400,000 volts are generated across its diameter. Such a large voltage could result in a large DC current flow.

The existence of such a current was suggested by observation some 15 to 20 years ago of very intense radio emission from Jupiter at frequencies ranging between 20 and 40



Taken one Jupiter rotation apart, these photos depict four days in the life of the Great Red Spot. Changes in circulation during the 40-hour period are clearly visible, particularly the flow of light material at the spot's right edge.

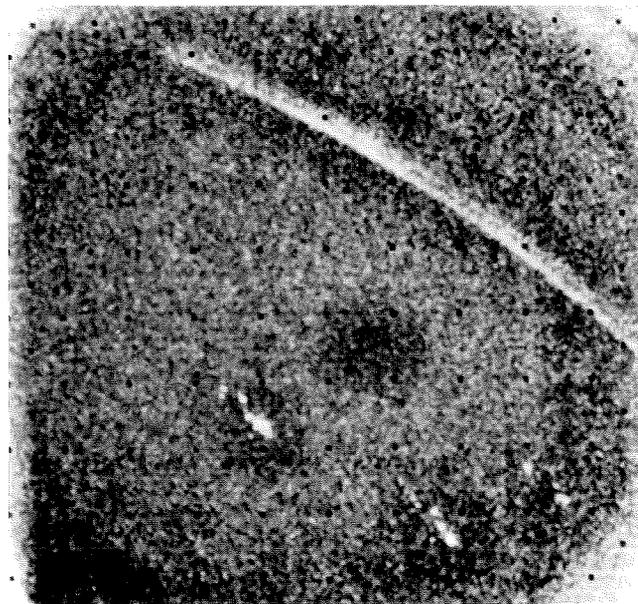
megahertz (just a little less than Channel 2). Whether or not the radio bursts were observed at Earth depended on where Io was in its orbit about Jupiter. That led to formulation of a model about 10 years ago by Peter Goldreich and R. M. Lynden-Bell that there was a large DC current flowing between Io and Jupiter, driven by the 400,000 volts across Io. When the current approached Jupiter, it generated radio waves. Goldreich and Lynden-Bell estimated that there might be a million amperes flowing from Io down the Jovian magnetic field to Jupiter, returning to Io along adjacent magnetic field lines much as the current to an electrical appliance flows along one wire in a lamp cord and returns in the other. The magnetic field lines along which the current flows are labeled the Io flux tube.

Voyager was targeted to fly through the flux tube in order to measure the current flow and thus confirm the nature of the interaction between Io and the magnetic field. Voyager did indeed fly through the targeted region, but there was so much current flowing along the flux tube that it was twisted by the current itself and displaced about 7000 km. So Voyager flew beside the flux tube, but was still able to measure the current, which was about five million amperes. Since the current in the flux tube is limited by the conductivity of Io and of Jupiter's ionosphere, it should eventually be possible to learn something about their electrical conductivity. Studying the physics of such a large rotating magnetic field and its interactions may also indirectly lead to a better understanding of the much larger, much faster rotating magnetic fields associated with pulsars.

There are other unusual aspects of the Jovian magnetosphere. For instance, Voyager discovered that the ultraviolet auroral activity (northern lights) was so intense that

it was easily observable in the daytime. The extent of the activity was indicated by a darkside image in which the visible auroral activity near the north pole extended across the entire frame, a distance of more than 30,000 km (18,000 miles). Terrestrial auroras are caused by the spiraling of charged particles from the Van Allen radiation belts along the magnetic lines of force into the atmosphere, causing the atoms to glow as in a neon lamp. Similar processes probably cause Jupiter's auroras but on a much larger scale. Further study of this enormous feature at Jupiter should provide information on large-scale magnetospheric processes that can be compared with the smaller scale processes on Earth.

There is another important result of the immersion of the satellites deep in the Jovian radiation environment. From ground-based observations it was known that there was a cloud of neutral sodium atoms that remained in Io's vicinity as Io orbited Jupiter. It was suggested that there were large salt flats on Io's surface from which the sodium was being ejected by the intense radiation bombardment. Pioneer had indicated that there might also be some neutral hydrogen associated with Io in its orbit, and other ground-based observations indicated the presence of singly ionized sulfur. As soon as any of these species became ionized (electrically charged), the ions would become attached to



This Voyager 1 image was taken of the dark side of Jupiter from a distance of 320,000 miles. The long bright double streak is an aurora near Jupiter's north pole. The other bright spots are probably lightning, and if that is what they are, the flashes are comparable to the brightness of superbolts seen at the tops of terrestrial tropical thunderstorms.

Jupiter's magnetic field, which rotates with Jupiter's 10-hour period. Since Io's orbital period is about 42 hours, the ionized particles are carried away from Io by Jupiter's rotating magnetic field and form a complete torus or doughnut around Jupiter. The singly ionized sulfur did appear to form such a torus with a temperature of about 10,000°K.

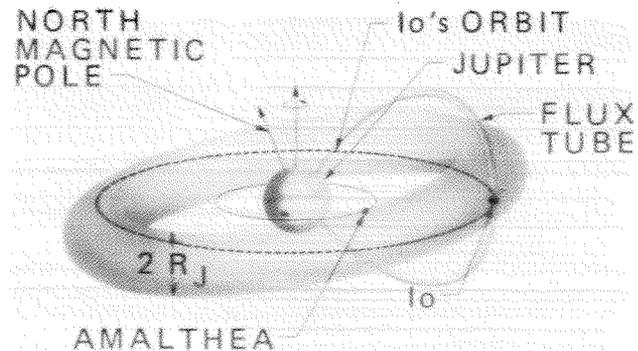
As Voyager 1 approached Jupiter, it was discovered that there was a much more intense ultraviolet emission from Io's orbit than had been observed by Pioneer in 1974. The emission was from doubly ionized sulfur and doubly ionized oxygen ions and indicated a temperature of 100,000°K in the torus. Since Pioneer had instruments sensitive enough to detect the same kind of radiation and saw nothing, there must have been a major change in the radiation and plasma environment around Jupiter since 1974.

Io is, of course, embedded in the torus and is presumably feeding the torus the material of which it is composed. As Voyager flew through the torus and under Io, it was possible to analyze the material directly. Sulfur, oxygen, and probably sulfur dioxide were identified. Though it couldn't be measured directly, there is likely hydrogen as well.

The Io torus thus appears to be a major link between the magnetospheric and satellite studies. The mechanism by which Io fed material into the torus was not immediately apparent. However, four days after the closest approach, with the discovery of active volcanoes on Io, it appeared that Io might be injecting into the torus such volcanic gases as sulfur dioxide, which would eventually be broken down into sulfur and oxygen, the ionized species that make up the plasma torus.

Unusual amounts of sulfur and oxygen are detected not only at Io, but right out to the edge of the Jovian magnetic field, and inward from Io as well. Inside of Io's orbit, the Voyager team led by Professor Vogt discovered that some of the oxygen, sodium, and sulfur ions have velocities greater than 10 percent of the velocity of light. The acceleration process by which ions from Io acquire such high velocities is the subject of more detailed study.

The torus, then, is the dense nucleus that feeds the rest of the magnetosphere with sulfur and oxygen — and probably also hydrogen. Possibly the torus material is coming out of the active volcanoes on Io, and perhaps the changes in the torus and the auroral activity since the Pioneer observations in 1974 are the result of changes in the volcanic activity. Certainly, if the volcanoes turn on and off, that could grossly affect the intensity of the plasma and therefore the intensity of the ultraviolet emissions. It could also affect the auroral activity. The difficulty with such a sim-



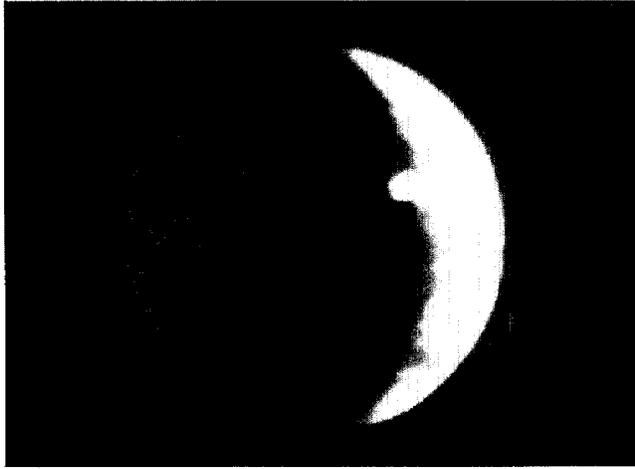
Jupiter is a ringed planet in more ways than one. First, it is orbited by a number of satellites; the paths of two of them — Io and Amalthea — are shown here. The large doughnut-shaped ring in which Io's orbit lies is a sulfur torus, with a diameter of $2 R_J$ (twice the radius of Jupiter) and a temperature of approximately 100,000°K. The magnetic field lines along which a five-million-ampere DC current flows from Io down to Jupiter and back again are called the Io flux tube. Not shown on this drawing, but in a circle inside Amalthea's orbit, is the thin layer of dark colored rocky material that Voyager 1 discovered orbiting Jupiter at about 35,000 miles above the cloud tops.

ple explanation is that since there were seven active volcanoes on Io during the Voyager 1 encounter, it's not easy to understand a possible cessation of volcanic activity in 1973-1974.

Although the observation of active volcanism was the most surprising Voyager 1 result, there was a calculation published shortly before the encounter which suggested that the heating due to the tidal distortions of Io's rocky crust would be sufficient to melt Io's interior. Like Earth's Moon, all four Galilean satellites, having long ago lost almost all of their rotational energy, are locked so that one side always faces the planet. If any one of them were a solitary satellite, it would probably — like Earth's Moon — have a permanent tide or distortion of its surface, slightly oblong and pointing toward its parent planet. But Io, the innermost Galilean satellite, is associated with three other large satellites, and the gravity of each of them exerts force on Io. When Europa and Ganymede are on the same side of Jupiter as Io, they pull Io slightly further away from Jupiter. When those two are on the other side of Jupiter, Io moves closer to Jupiter a small amount. As Io is pulled in and out, the tide in the rock crust changes by up to 80 meters. Such recurrent tidal stretching heats Io much as a piece of metal is heated by repeated flexing. Although continuous tidal dissipation could eventually cause Io to spiral into Jupiter, evidently the rotation of Jupiter itself is pumping energy back into Io's orbital motion. Thus the ultimate source of energy for the continued volcanic activity on Io may well be Jupiter's rotational energy.

As interesting as Io is, it is just one of four major satel-

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Taken for navigational purposes, this picture of Io is nevertheless one of the most scientifically exciting of all of the thousands of images returned to Earth by Voyager 1. It gave the first proof of volcanic action on Io and set scientists to reexamining other photos — eventually to come up with evidence of seven active volcanoes on the satellite and a possible explanation for how Io feeds material into the sulfur torus. In this photo, one volcano can be seen on the limb, with ash clouds rising more than 150 miles above the surface. The second volcano is the bright area on the terminator, where the volcanic cloud is catching the rays of the rising Sun.

lites that are the subject of the third major area of Voyager studies. As Galileo first observed, the four satellites — two of which are about the size of the Moon and the other two similar in size to Mercury — form a miniature solar system about Jupiter. There is an important similarity between the solar system and the Galilean system that Galileo could not have known. The inner two satellites, Io and Europa, are dense rocky objects, as are the inner planets, while the outer two satellites, Ganymede and Callisto, are low-density objects, as are the outer planets. Thus there are two systems in which the formation of secondary bodies about a primary can be studied.

The outermost Galilean satellite, Callisto, has a density less than twice that of water, suggesting that it may be half water or ice. Callisto has the oldest surface, probably four billion years old. It is very dark colored, possibly a mixture of rock and ice. The surface is heavily cratered, with one huge ghost of an impact crater, which is a series of fairly regularly spaced concentric circles. The very regularity and spacing of these rings will provide information about the mechanical properties of the material at the time of impact. Callisto's surface evidently has not been significantly modified by internal processes.

Although Ganymede is almost the same size and density as Callisto, there is clear evidence that its surface has been severely modified by internal processes. There are large

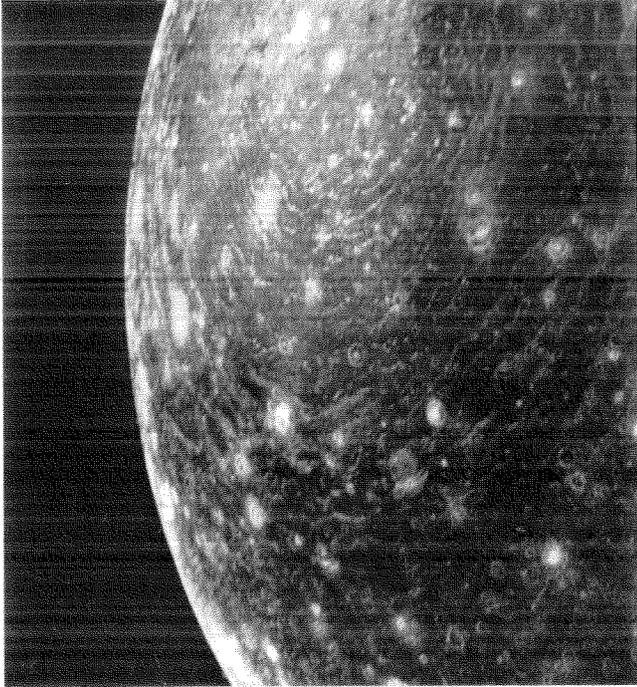


From a distance of 18,480 miles, one of Io's volcanic craters looks like this. The region in the photo is about 147 miles wide, and the caldera itself is about 30 miles in diameter, with dark flows of lava radiating from its rim. Some of the flows are over 60 miles long and almost 10 miles wide. Similar but smaller flows and craters occur on the island of Hawaii.

dark areas that are older, separated by lighter, younger highly striated regions, as though it were ice under compression. There appears to have been some internal process that has resulted in the movement of the darker regions around on the surface in a way that may have some similarity to continental drift here on Earth. Thus the evolution of Ganymede and Callisto has been quite different and will be studied in detail.

Since Voyager 1 did not fly close to Europa, there is currently less known of this satellite, which is similar to Io in size and density and orbits Jupiter between Io and Ganymede. Europa is a rocky body with a thin ice crust that is marked by long curvilinear streaks that are 50 to 200 km wide. These streaks may be large cracks in the glacial cover, perhaps extending into the rocky surface itself. There are at least two ways such cracks might occur. One is that tidal forces pulling on the satellite caused cracking of the surface long ago. Another is that Europa, like Io, is internally active, and the cracking is evidence of continuing internal thermal activity. Of course, the streaks may not be cracks. Voyager 2 will fly much closer to Europa in July and should greatly improve our knowledge of this fourth different Galilean satellite.

Voyager 2 should also provide more information about the ring discovered around Jupiter about 35,000 miles above the cloud tops. A number of additional images have

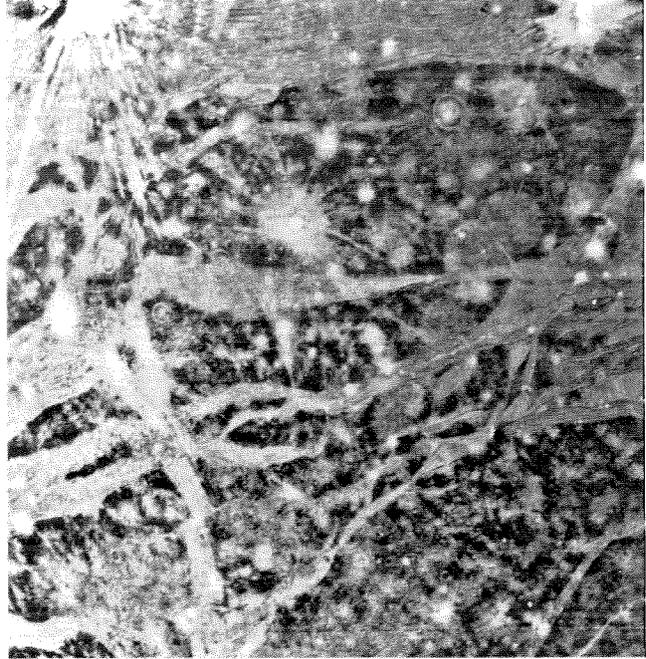


Heavily cratered Callisto is the outermost and darkest of Jupiter's satellites and probably has the oldest surface. It is thought to have a rocky or muddy core with an icy crust. Most of its craters are from 12 to 30 miles wide, but one exception is the huge impact basin at the upper left. The basin is more than 370 miles wide, and its concentric rings extend outward more than 800 miles. The ripples probably were formed as the fragile, icy crust heaved under the impact of a large meteorite and then quickly froze again. Incidentally, dark as Callisto appears, it is still more than twice as bright as our Moon and considerably larger — about the size of the planet Mercury.

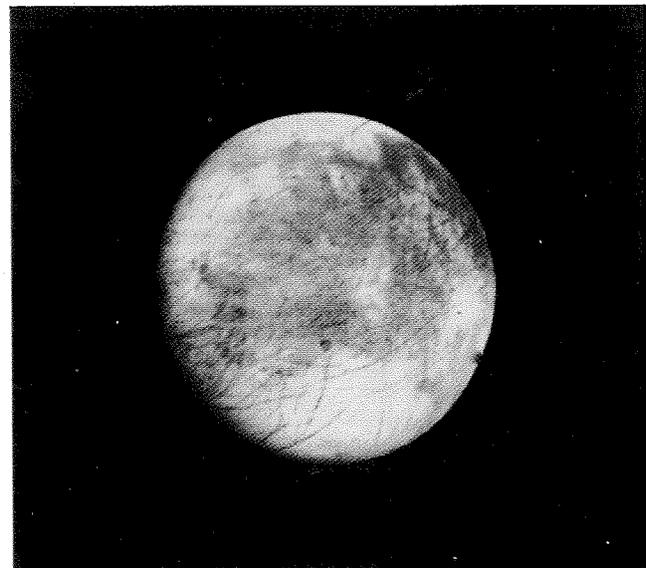
been scheduled in order to determine the inward radial extent of the ring, which seems to be a very thin layer of dark colored rocky material. It's interesting that this is the third giant planet with a ring, leaving Neptune the only one without a known ring.

Voyager 2 will also take a series of images of Io over a 10-hour period so that time-lapse sequence of the volcanic plumes will be available for study of the variability of the volcanic processes. Much more extensive darkside imaging of the lightning and auroral activity on Jupiter is planned for Voyager 2, which will also provide closeup views of the sides of Ganymede and Callisto that were not viewed closely by Voyager 1.

Both Voyager 1 and 2 will continue on to Saturn, arriving in November 1980 and August 1981, with an option to send Voyager 2 on to a January 1986 encounter with Uranus. Thus, the Voyager 1 encounter with Jupiter is just the first of a series of encounters with the many different and surprising worlds in the outer solar system. □



The largest of the Galilean satellites is Ganymede, which is about 1.5 times the size of our Moon and about half as dense. It has numerous impact craters, many with extensive bright ray systems. A bright band trending in a north-south direction in the lower left-hand portion of this picture is offset along a bright line. This offset is probably due to faulting, and this is the first observation of such a fault anywhere in the solar system outside Earth.



The long linear structures that criss-cross the surface of Europa could be faults or fractures. Some of these features are as much as 1000 miles long and 125 miles wide. Voyager 2 is expected to furnish considerably more detail about this smallest of the Galilean satellites.