Io: Jupiter's Enigmatic Moon

by Torrence V. Johnson

THE WHITE QUEEN SAID to Alice, "Why, sometimes I've believed as many as six impossible things before breakfast." Meeting this quota is no problem if you merely whisper to yourself every morning — "Io exists!"

Scientific study of Io began in 1610 with its discovery by Galileo, along with the other three large moons of Jupiter — Europa, Ganymede, and Callisto. This article almost had a very different title, since Galileo proposed calling these new objects the "Medici stars." Acknowledgement of funding sources was as important then as now. It was Kepler and Simon Marius (who also claimed to have discovered the moons) who suggested naming them after Jupiter's lovers. They are now known collectively as the Galilean satellites.

In 1675 the Swedish astronomer Ole Roemer noted that the intervals between Io eclipses were shorter when the Earth was moving towards Jupiter than when it was moving away. The accumulated lag from one side of Earth's orbit to the other was about 16 minutes. Roemer deduced that this was due to the finite speed of light, which Galileo had tried unsuccessfully to measure, and calculated the first accurate value for this fundamental quantity.

Studies of the satellites of Jupiter continued to be of importance to the growing science of astronomy. In the 1890s A. A. Michelson tested his stellar interferometer by measuring the diameters of the Galilean satellites, values that are within 20 percent of the modern numbers in most cases. In the early part of the 20th century, the mathematical problem of describing the effects of mutual gravitation among the satellites on their orbits was solved, providing fairly accurate estimates of their masses.

In the latter half of the century, increasingly sophisticated astronomical observations continued to reveal strange things about the moon Io: its influence on the probability of certain types of radio noise outbursts from Jupiter; its yellow, highly reflective surface; and its "pollution" of the whole Jovian magnetosphere with clouds of atomic material.

All the studies from the time of Galileo until just a few years ago were limited to observations of a tiny spot of light in our telescopes. Detailed study of Io began with the first spacecraft observations by Pioneer 10 in

MOON

IO EUROPA GANYMEDE CALLISTO

MERCURY
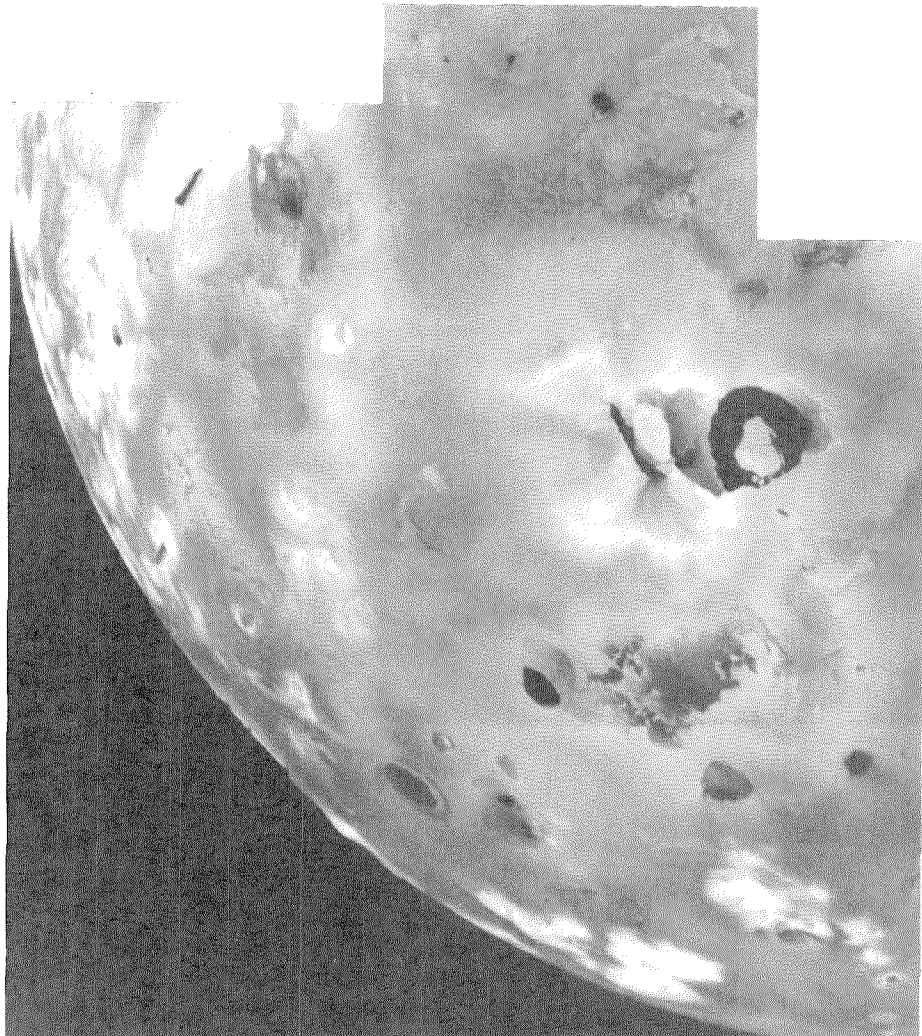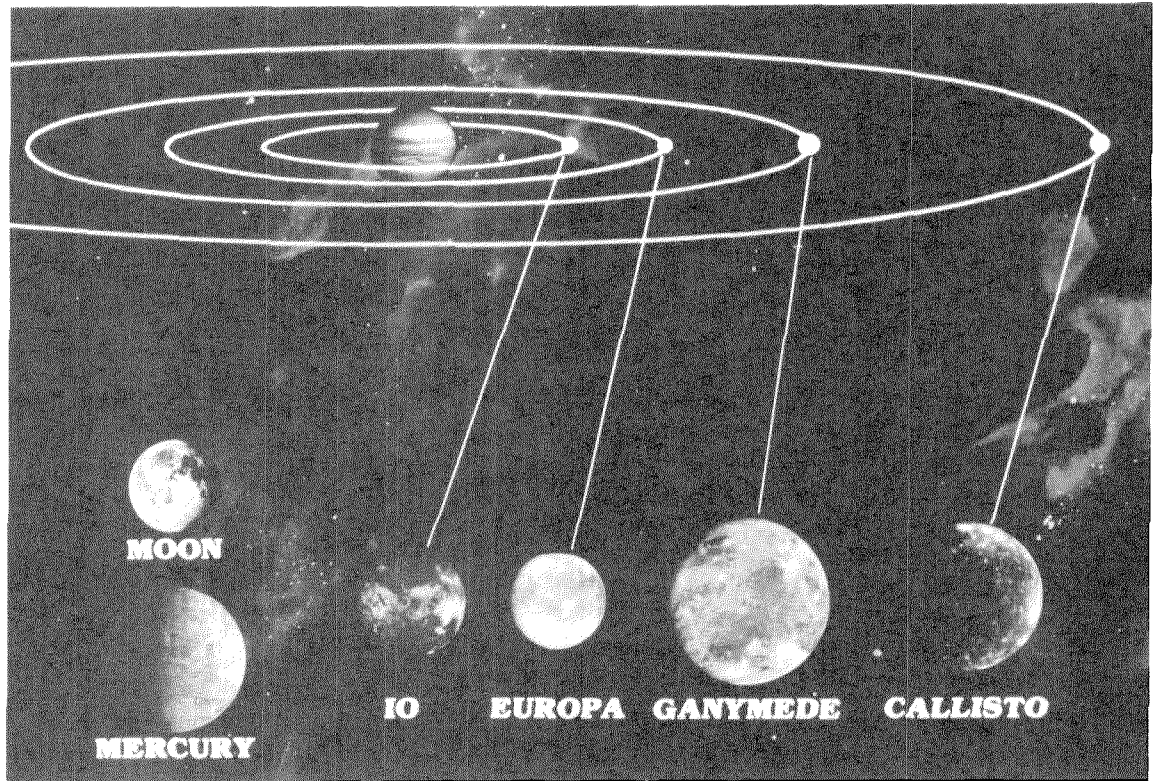
Io, the closest to Jupiter of the Galilean satellites, is almost as large as our Moon.

1973, which discovered evidence of a layer of electrons and ions high above Io's surface, suggesting at least a tenuous gaseous atmosphere of some type. Just a few years later, in 1979, our eyes were opened by the spectacular results of the Voyager flybys, which showed Io to be a world even stranger than most of us had imagined. Just how strange may be judged by the fact that even Arthur C. Clarke in his science fiction novel *2010* found Io entirely weird enough as it is and didn't embellish its nature at all.

Jupiter and its system of moons is five times farther away from the Sun than the Earth is. Io is about as far away from Jupiter as the Moon is from the Earth. This means that in Io's sky, the Sun is only a fifth the size that we are accustomed to, while Jupiter looms 40 times larger than the full Moon. Because the amount of solar energy reaching a planet decreases as the square of its distance from the Sun, Io receives only 1/25th the solar energy that the Earth does, and it's very cold. Noon temperatures on Io's equator do not rise above about -130° C, or about -200° F, and night temperatures drop to below -170° C, or about -300° F.

The Galilean satellites are relatively large objects (Io is the size of the Earth's Moon). Ganymede and Callisto are made of mixtures of ice and rock, but Io has a density a little heavier than the Moon's and must therefore be composed primarily of rock. But Io's yellow, reflective surface doesn't *look* anything like that of the Moon, the planets, or the other Galilean satellites. We believe that coatings of sulfur-rich compounds are responsible for its appearance. Solid sulfur dioxide has been identified in the spectrum of Io's surface, and sulfur dioxide gas was detected over one of Io's big volcanoes by instruments on the Voyager spacecraft. Elemental sulfur may be responsible for the odd coloration of much of the surface.

The most surprising feature of Io's surface is that it's geologically young and volcanically active. Instead of having the numerous impact craters formed when meteorites strike most planetary surfaces, Io's surface is covered with a variety of volcanic landforms and large eruptive plumes. But how did these peculiarities of Io's surface come about?

Since Galileo's time the Jupiter satellite system has been popularly thought of as a miniature solar system, and there are indeed many points of similarity. We believe that the planets in the solar system formed from material condensed from a cloud of gas and dust with the same overall composition as the Sun has now. In most current theories of cosmogony, the distance from the Sun in this nebula controls the composition of the solid material available to make up planetary objects, with rock and iron dominating the

planets of the inner solar system and increasing mixtures of frozen volatile materials, primarily water ice, those beyond the asteroid belt.

The smaller, inner planets, such as the Earth and Mars, were probably unable to alter the conditions around them substantially from the general conditions prevailing in the nebula during formation. Jupiter, however, was massive enough to create a microenvironment in the solar nebula. As material gathered about Jupiter, gravitational contraction heated it to very high temperatures. Even today, the remnants of that early heat are leaking out from Jupiter's deep interior, so that the planet radiates almost twice as much energy as it receives from the Sun. Many theorists believe that this circumstance accounts for the lack of large quantities of ice on Io and Europa compared with Ganymede and Callisto — it was just too hot close to Jupiter for ice grains to survive and be collected into the forming satellites. Not all scientists accept this simple view, and Jupiter's role in focusing incoming debris into an intense collisional environment in the inner part of the satellite system has been suggested as a major modifier of the moons' early development. In any case, it seems clear that in the early formation stages of Jupiter and its moons the regions close to the giant planet differed significantly from the outer regions, helping to create the diversity of satellite compositions and characteristics we see today.

The life history of a planetary body is controlled by its energy balance. For most bodies, the energy coming from the sun is negligible in this balance in terms of its geological effect. The three main energy sources that control the evolution of most planets are the energy of formation, the energy from the decay of short-half-life radioactive elements, and the energy from the decay of long-half-life radioactive elements. The first two generally affect only the early history of a planet. The third is believed to be responsible for the current level of geological activity in most terrestrial planets.

The most important long-lived radioactive elements are uranium, potassium and thorium. These provide a heat source that builds up over billions of years, keeping the internal fires of the planet alive. Just how active a planet will be under the influence of this energy input is primarily a function of how fast it can lose the heat being generated in its interior; this heat is carried to the surface of the planet by a variety of processes and ultimately is radiated away into space. The efficiency of heat loss is tied to the surface area of the planet, while the amount of heat generated is linked to the planet's volume. This creates a situation that greatly favors big planets over small ones in the geological activity sweepstakes. The simple principle that bigger is hotter works admirably for the Moon, Mars, Earth, Venus, and Mercury. So we didn't expect active volcanoes on Io; we thought it had been geologically dead for more than 3 billion years, similar, in fact, to our own Moon.

There turns out to be, however, another source of energy that might drive current activity — tides. The story of how tides can heat a satellite, why this source was overlooked for so long, and how tidal heating might drive Io's volcanoes is an interesting one. First of all, if you think of tides as something only associated with the Earth's oceans and think of the gradual ebb and flow of the water down at the beach, you might not be inclined to think of tides as very important as sources of planetary heating. To really understand tides as important planetary forces, you have to consider three facts: tides affect all gravitating bodies; tides are raised in the entire body of a planet, solid as well as liquid; and the only way to get work out of tides is for them to change.

It is this third point that is responsible for the effects of tides on Io being overlooked for so long. If a moon is in circular orbit and is spinning at the same rate that it circles its planet, the net result is no change in tides. Io's orbit, averaged over a long time, is almost exactly circular, and its rotation is exactly the same as its orbital period. So no one worried much about tidal heating on Io, even though the idea had been kicked around as a heat source for our Moon, where the tides do change due to its noncircular, eccentric orbit.

The moons of Jupiter, however, are big enough to influence each others' orbits. This continual gravitational jostling has resulted in a relationship between the satellites' orbital periods, an effect first studied by the French mathematician Laplace. Europa, the next satellite out, orbits Jupiter with a period almost exactly twice that of Io, so the distance between Europa and Io varies in a systematic way, being at a minimum every two Io periods. Europa is very small compared to

Jupiter, and its gravitational pull is less than one ten thousandth of Jupiter's, even at its closest. So it doesn't do anything important itself in terms of tides. But the fact that it varies so regularly is extremely important. Essentially, every two Io orbits Io gets a small kick from Europa, always in the same place. This is known in physics as a resonance phenomenon; it's similar to giving a pendulum a small push, always at the same place in its swing. This will cause the amplitude of the swing to build up rapidly, just as a child on a playground swing can pump its legs in rhythm with the motion to go higher and higher. The result of this is that Io's orbit is not quite circular; it has a "forced eccentricity" of 4 parts in 1,000, enough to change the tides.

The tides on Io change in two important ways. First, since Io in its eccentric orbit is a little closer to Jupiter on one side of its orbit than on the other, the tidal force changes, and the deformation due to the tide goes up and down by about 100 meters as Io revolves in its orbit. Second, Io keeps spinning at a constant rate, but changes its speed as it goes around Jupiter in accord with Kepler's laws; this causes the point where the tide is maximum to wobble back and forth across the surface in the course of Io's orbit. Both of these changes translate into heat by creating friction in the crust and interior.

The implications of Europa's orbital *pas de deux* with Io were not realized until just before the Voyager encounter. Only weeks before the Voyager 1 encounter in 1979, an article by Stan Peale at UC Santa Barbara and two colleagues at Ames Research Center was published in *Science*, suggesting that Io may get more heating from tides than from radioactive isotopes. Peale and co-workers suggested that some volcanic features might be present on Io — a prediction amply
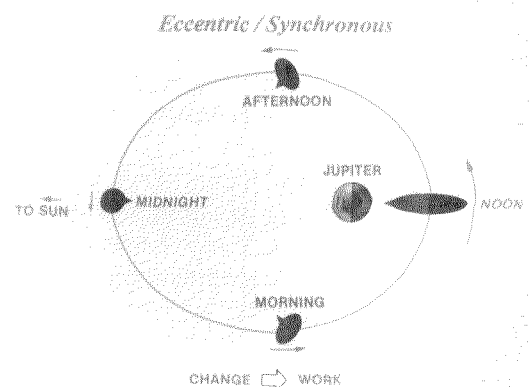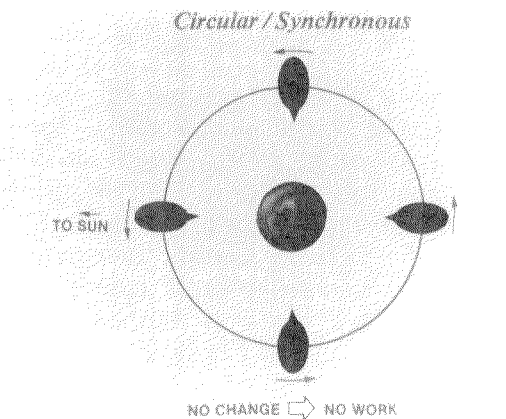
confirmed by Voyager's pictures.

Even Voyager's first, long-range views of Io showed us that we were dealing with a very young surface. Io displayed no hint of impact craters or basins, unlike virtually all other planetary surfaces. And, as Voyager approached Io, we could see features that were clearly volcanic in nature, quite reminiscent of the volcanoes on Hawaii, seen from an airplane, but on a much larger scale.

Finally came the discovery of some sort of active eruptions on Io. This was the real shocker. What was actually seen was what we now refer to as a "plume." Linda Morabito, a navigation engineer at JPL, found it on a deliberately overexposed picture a few days after the encounter; others were independently discovered by the imaging team the next week while reviewing the raw data.

There has been a lot of confusion about what constitutes a "volcano" on Io. Volcanoes on the Earth usually have large volcanic collapse craters known as calderas in the tops of high mountains. Eruptions cause lava flows, which cascade down the side of the mountain and throw large amounts of gas and ash up into volcanic clouds or plumes. Io has high mountains, large calderas, lava flows, and plumes, but they are not related in the same way that they are on the Earth. The calderas are not in the tops of mountains; in fact we don't know for sure what builds up mountains on Io. The lava flows we see are not connected with the currently active volcanoes. The plumes we see are more likely to be giant geysers, driven by volcanic heat but not due to volcanic dust and lava thrown into the air.

When we first saw the pictures of plumes on Io, our initial thought was that we were looking at large-scale explosive eruptions, similar to Vesuvius or Mount St. Helens. As with many quick intuitive ideas in science,

If Io's orbit were circular, its internal heat would be too low to produce its high geological activity. But the tiny "kick" it receives from Europa puts it in a slightly eccentric orbit. The tides produced in this way translate into heat by creating friction in its crust and interior.

Circular / Synchronous

TO SUN

NO CHANGE ⇨ NO WORK

Eccentric / Synchronous

AFTERNOON

TO SUN   MIDNIGHT   JUPITER   NOON

MORNING

CHANGE ⇨ WORK

the rub came when we tried to plug numbers into this idea. There were two primary problems to be addressed — the size of the plumes and their long lifetimes. The observed plumes range from about 80 km to over 300 km in height, and most of them seem to have continued their eruptions over at least the four-month interval between the two Voyager encounters.

Io has essentially no atmosphere to impede the flight of volcanic debris, and its gravity is low — about one-sixth of the Earth's. Under these conditions, we expect material ejected from a small vent area to spread out in a nice symmetrical umbrella-shaped plume with each particle following a ballistic trajectory. Using simple ideas of ballistic flight, we can estimate the required exit velocities for particles at the base of the plume that will allow them to reach the observed height and range.

A typical plume on Io requires very high ejection velocities; a velocity of over 1 km/sec (greater than about 2,000 mph) is needed to match the largest plumes. Although typical volcanic ejection velocities on the Earth are far below this, some terrestrial explosive volcanism, such as massive steam explosions, can just about reach the necessary velocities. These events are usually very brief, however, lasting hours or a few days at most. Driving Io's plumes to such high velocities over periods of at least several months seems to require a totally different type of mechanism.

The answer seems to be that the plumes are, in fact, more like geysers. Geysers result when a fluid is heated at some depth below the surface and then is allowed to expand upward through a narrow vent to the surface — somewhat similar to a rocket exhaust. Geysers aren't very large or impressive on the Earth; even Old Faithful rises only about 30 meters from the surface during an eruption. The conditions are very different on Io. On Earth the geyser has to fight six times greater gravity, and it expands upward into a thick atmosphere. Sue Kieffer (PhD 1971) of the U. S. Geological Survey has studied both Old Faithful and Mount St. Helens in detail. She notes that if Old Faithful were placed on Io, it would erupt to a height of about 38 km — small by Io's standards but still impressive enough.

But what makes Io's geysers work? There is no trace of water in the spectrum of Io's surface or its tenuous atmosphere; a different working fluid is required to make the system
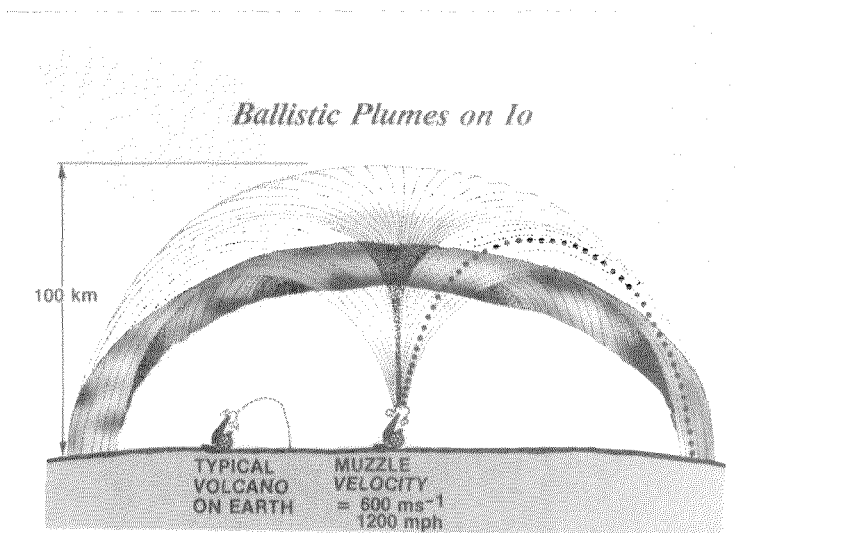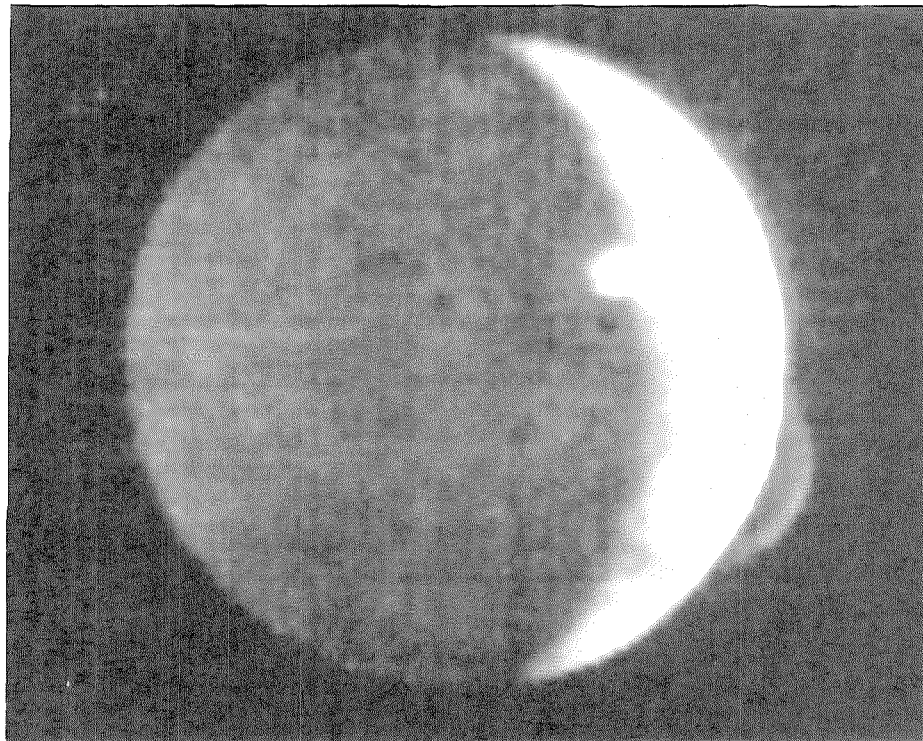
go. The best candidates are sulfur dioxide and sulfur itself. Although both these substances are solid on Io's surface, they become liquid at relatively shallow depths in Io's volcanically heated crust. If liquid sulfur dioxide, at a depth of about 500 meters, comes into contact with either hot liquid sulfur or volcanic hot rock, it first begins to boil as it expands up the conduit to the surface; then, as the pressure and temperature drop lower and lower, solid sulfur dioxide will begin to "snow" out of the rising column as it reaches the surface. Kieffer and her colleagues have

Ballistic Plumes on Io

100 km

TYPICAL VOLCANO ON EARTH   MUZZLE VELOCITY = 600 ms⁻¹ 1200 mph

JPL navigation engineer Linda Morabito first noticed Io's volcanism on this intentionally overexposed Voyager 1 photograph (top). In the diagram below, the ballistic plumes on Io are shown to be symmetrical, umbrella-shaped, and far larger than Earth's largest volcanoes.

Evolution of a Sulfur Dioxide Geyser
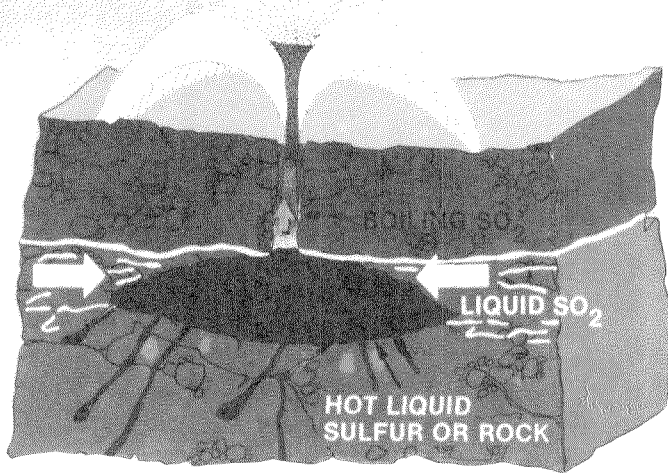
Io's sulfur geysers are thought to originate when liquid sulfur dioxide boils at a depth of 500 meters. As it expands up a conduit to the surface, the temperature and pressure drop and solid sulfur dioxide "snows" out (above). The Loki caldera is shown below to scale with an earthly volcano (Hawaii).

calculated that a system such as this can easily achieve the exit velocities of 500 to 600 m/sec required to match typical plume characteristics. Even higher velocities can be reached if the sulfur dioxide is heated to higher temperatures, or if the fluid is sulfur heated by contact with hot rock.

Next to the plumes, the most prominent volcanic features on Io are the many large calderas. Maasaw Patera, one of Io's medium-sized craters, is similar in dimensions to the summit area of Olympus Mons, the giant Martian volcano, but as far as we can tell, this crater and most others on Io are on fairly level volcanic plains. One of the most impressive and strangest features on Io is the Loki caldera. The size of this feature, over 200 km across, dwarfs the summit crater of even Olympus Mons. The Loki caldera, instead of being a deep hole in the ground, seems to be filled with darker material, presumably lava of some sort, although there are no obvious flows leading away from the edges.

Loki was the site of two other important Voyager discoveries. The Voyager infrared instrument found that this whole area was much hotter than its surroundings; much of the dark area is about room temperature instead of the usual frigid -200° F, and some portions of it are hotter than boiling water. In addition, spectra obtained by the infrared instrument showed the presence of small amounts of sulfur dioxide gas above Loki, the only direct evidence that we have for the composition of gas in Io's tenuous atmosphere. Loki is also the site of one of the active plume eruptions seen by Voyager. In many ways the Loki feature resembles an active lava lake, although of stupendous proportions. The amount of heat radiated from Loki accounts for about half of the total heat energy leaving Io through its volcanoes.

Loki and other active hotspots are hot enough relative to their surroundings that we can detect their presence even from the Earth. When we measure the infrared radiation coming from Io, we find that the flux between wavelengths 5 and 10 microns comes primarily from volcanic emissions. By measuring the variation of this flux as Io rotates, our group, in cooperation with scientists from the University of Hawaii, has found that Loki is still active and probably is one of the most important heat sources on Io.

There are two major unresolved problems associated with the calderas and the hotspots

(the volcanically active areas): How much total heat is coming from Io compared with what is being put in by tidal heating? And what is the material in the calderas — sulfur or molton rock? When all the volcanic sources in our models are added up, Io's total heat output is about 10^{14} watts — an astounding figure. We thought that tidal heating must account for the volcanic activity levels on Io, but even this source has some limitations. The best theoretical estimates of these limits say that if Io has been heated by tides for the last 4.5 billion years, the average rate of energy input over that period can only be about one-half of the observed infrared power being radiated. This is an energy crisis in reverse. There are several possible solutions to this problem. There might be a flaw in the theoretical arguments from which the limit on tidal energy input is derived; we might be wrong in our estimate of the total power of volcanic sources that were not observed directly by Voyager; or Io may not always be as active as we see it now. Some interesting work on this last possibility is being done by Dave Stevenson, associate professor of planetary science, and graduate student Greg Ojakangas. They are developing a theory that suggests that the amount of tidal energy that can be turned into heat varies with time due to changes in the properties of rock as it becomes partially molten. In this theory Io becomes, in effect, a huge thermal oscillator, which is currently in a relatively hot state, but which has an average heat output over geological time that would satisfy the lower theoretical limits. There is a lot more work to be done with both observations and theory before we have a final answer to this problem.

The second unresolved problem associated with the calderas and hotspots is the debate about sulfur versus silicate volcanism, which goes back to the basic fact that Io's density indicates that it is made mostly of rock, while its surface layer seems to be dominated by sulfur compounds. Molten rock, heated by the friction of tidal changes, must be the ultimate source of volcanic activity on Io. The only question is whether most of what we see is more or less ordinary volcanism, colored by small amounts of sulfur, or whether the molten rock heats up large masses of sulfur, resulting in sulfur volcanic flows or calderas full of liquid sulfur rather than silicate lava. Certainly the mountains we see and the deep volcanic craters in some areas must be features in a relatively hard silicate rock crust;
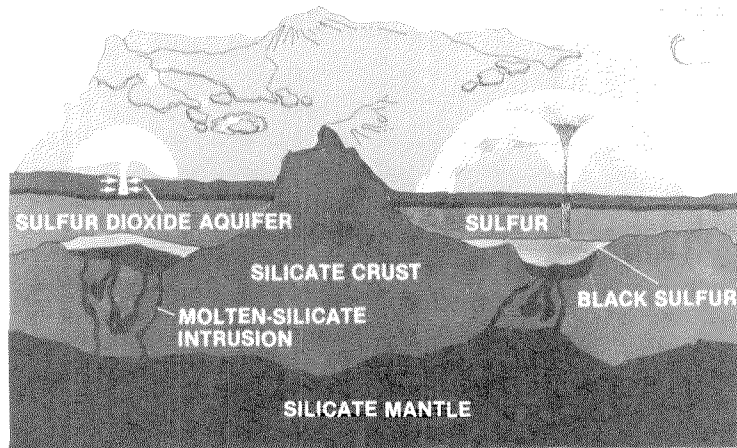
a deep surface layer of mostly sulfur would not be strong enough to support these features.

In support of the idea of at least some sulfur volcanism is the fact that the hotspot temperatures measured by Voyager and inferred from various telescopic measurements are too low to indicate the presence of large amounts of molten rock in the hotspot regions. On the other hand, these temperatures are quite reasonable for various forms of molten and cooling sulfur. In my opinion, silicate volcanism occurs on Io, and many of the lava flow features around calderas such as Maasaw are probably flows of rock lava. However, the continuous heat-producing areas associated with the dark calderas may very well be examples of large pools of molten sulfur heated from below by deeper seated silicate volcanism.

One of the consequences of volcanic heating is the large amount of material involved in resurfacing the moon, as indicated by the absence of impact craters on Io. Craters must be buried more rapidly than they are formed, leading to the conclusion that about one millimeter of new material must be added to Io's surface every year. This translates into an eruption rate of at least several thousand tons per second, and the actual rate may be even higher. At this rate Io's volcanoes have to put out as much material every month as was involved in the massive explosion of Mount St. Helens.

Over geological time the eruption rates implied by Io's lack of impact craters suggests that at least the upper portions of Io's interior

Io is composed mostly of silicate rock, but its surface is dominated by sulfur compounds. It's still uncertain whether the volcanic flows are made of liquid sulfur, or whether they are made of silicate lava colored by small amounts of sulfur.

have been heated, brought to the surface, buried, and reheated many times. This probably explains the lack of any water ice on Io's surface; even if Io originally formed with some ice or water incorporated in its rocks, this continual heating and recycling of the crustal material would have sweated out all the water, which would have broken apart into hydrogen and oxygen and subsequently escaped to space. Sulfur, although volatile, is harder to get rid of than water, and so we might expect a buildup of sulfur-rich material in Io's crust over time, making all of Io's surface one huge geothermal-type mineral deposit.

Another consequence of the volcanic activity is that volcanic gases, particularly sulfur dioxide, are continually being supplied to the surface to form a tenuous atmosphere. Sulfur dioxide will freeze at noontime temperatures on Io's equator, but even though it is very cold, there will always be some amount of gas evaporating from this frost and forming an atmosphere. This idea is quite similar to the one that Bob Leighton, the William L. Valentine Professor of Physics, and Bruce Murray, professor of planetary science and former director of JPL, came up with after the first Mars mission to explain that planet's carbon dioxide atmosphere and its relation to the polar caps. The major difference here is that while Mars has a surface pressure a few thousandths of that of the Earth's, Io has a maximum possible atmospheric pressure from this source of less than one ten-millionth of the Earth's. An atmosphere this thin is just a short step away from being a pretty good vacuum, but it is still thick enough to be interesting. Another difference is that the sulfur dioxide frost is stable all over the planet, not just in the polar regions, as is the case with carbon dioxide on Mars.

One of the things we do know about the fate of material brought up by Io's volcanoes is that at least some of it escapes from Io and forms a potent source of charged particles in Jupiter's radiation belts. Before Pioneer and Voyager it was expected that most of the particles in the radiation belts would be protons and electrons, with a small amount of heavier elements. When Voyager measured the composition of the radiation belt particles, we found that instead of hydrogen nuclei, most of the positive ions were sulfur and oxygen nuclei, with a little sodium and potassium thrown in. This material must have had its origin at Io.

Voyager's ultraviolet spectrometer was able to detect a huge doughnut-shaped region, known as the Io torus, following Io's orbit. It's filled with sulfur and oxygen atoms emitting intense ultraviolet radiation. We can also see some of this material from the Earth. We don't know exactly how material escapes from Io, but it is probably kicked off the surface and out of the atmosphere by the impact of other particles in the radiation belts. A lot of the material probably comes off Io as neutral atoms, which are then later stripped of some of their electrons by other radiation belt electrons. Fortunately, Io provides us with tracer atoms, which, although they are less abundant than the sulfur and oxygen atoms, can easily be seen from the Earth. These tracers are sodium atoms, which glow brightly in sunlight, emitting two intense spectral lines. These sodium emissions were first detected several years before the Voyager encounters, but their full significance was not realized until they were placed in the context of the Voyager discoveries and other studies of the torus.

The next step in understanding Io will come in 1988 with the Galileo mission. The Galileo spacecraft, which is currently being built at JPL, will be launched from the space shuttle in May 1986. When it arrives in December 1988, it will spend another two years orbiting Jupiter (it will pass Io at an altitude of 1,000 km, 20 times closer than Voyager) sending back data that should help solve some of the mysteries of Io I have mentioned here — and will almost certainly deliver still more surprises. □

Sulfur and oxygen atoms escape from Io's surface, producing a torus around Jupiter.