The Galileo Mission to Jupiter and Its Moons

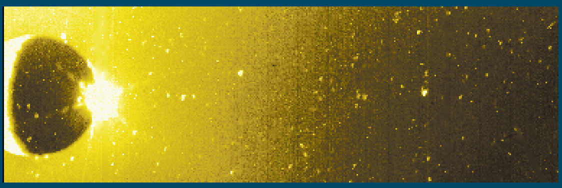
Few scientists thought that the Galileo spacecraft, beset by technical troubles, could conduct such a comprehensive study of the Jovian system. And few predicted that the innards of these worlds would prove so varied

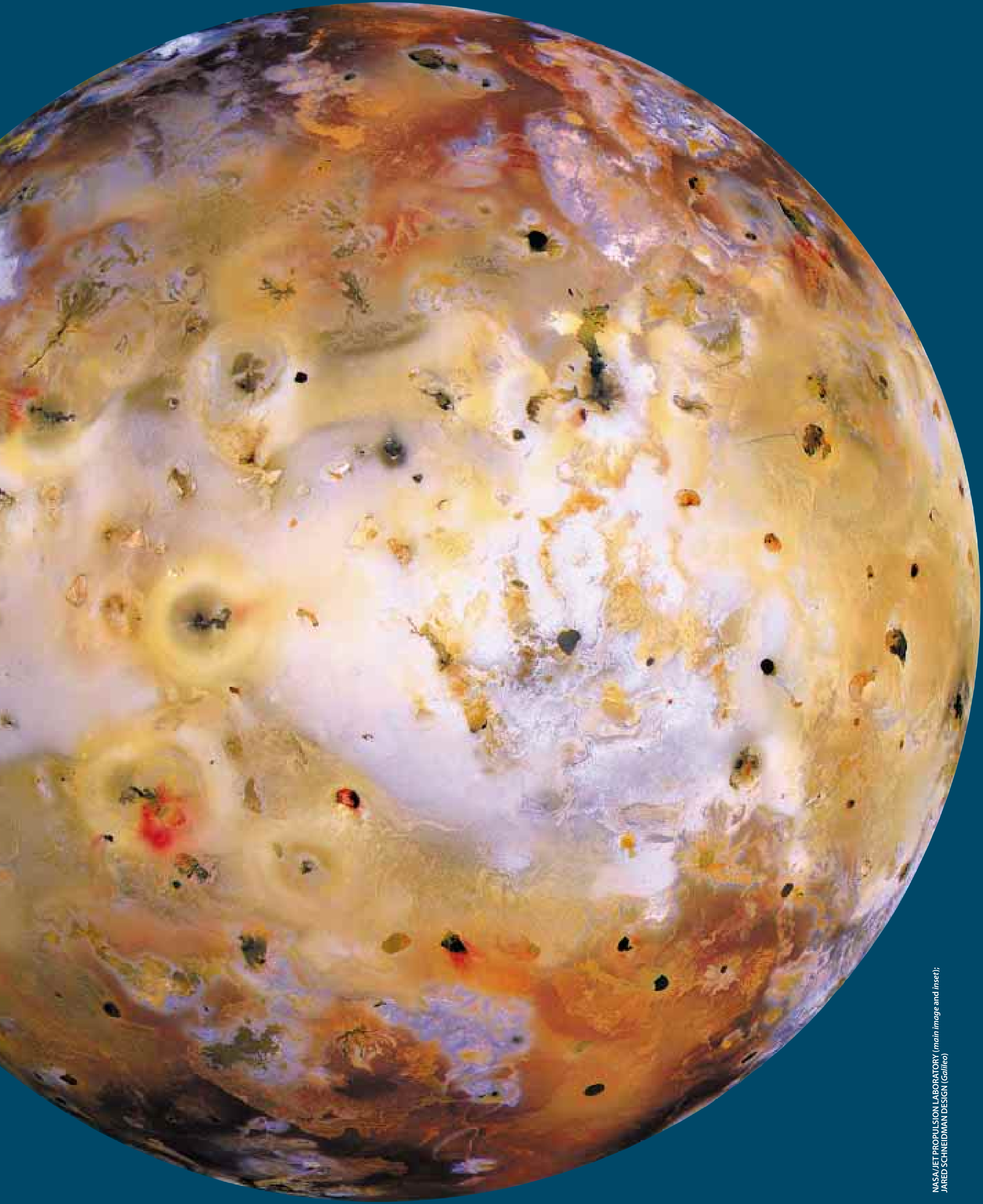
by Torrence V. Johnson

To conserve power, the probe was traveling in radio silence, with only a small clock counting down the seconds. Racing 215,000 kilometers overhead, its companion spacecraft was ready to receive its transmissions. Back on Earth, engineers and scientists, many of whom had spent most of two decades involved in the project, awaited two key signals. The first was a single data bit, a simple yes or no indicating whether the little probe had survived its fiery plunge into Jupiter's massive atmosphere.

Getting this far had not been easy for the Galileo mission. When conceived in the mid-1970s, the two-part unmanned spacecraft was supposed to set forth in 1982, carried into Earth orbit on board the space shuttle and sent onward to Jupiter by a special upper rocket stage. But slips in the first shuttle launches and problems with upper-stage development kept pushing the schedule back. Then came the *Challenger* tragedy in 1986, which occurred just as Galileo was being readied for launch. Forced by the circumstances to switch to a safer but weaker upper stage, engineers had to plot a harrowing gravity-assist trajectory, using close flybys of Venus and Earth to provide the boost the new rocket could not. From launch in October 1989, the journey took six years. Two years into the flight, disaster struck again when the umbrellalike main communications antenna refused to unfurl, leaving the spacecraft with only its low-capacity backup antenna [see "The Galileo Mission," by Torrence V. Johnson; Scientific American, December 1995]. Later, the tape recorder—vital for storing data—got stuck.

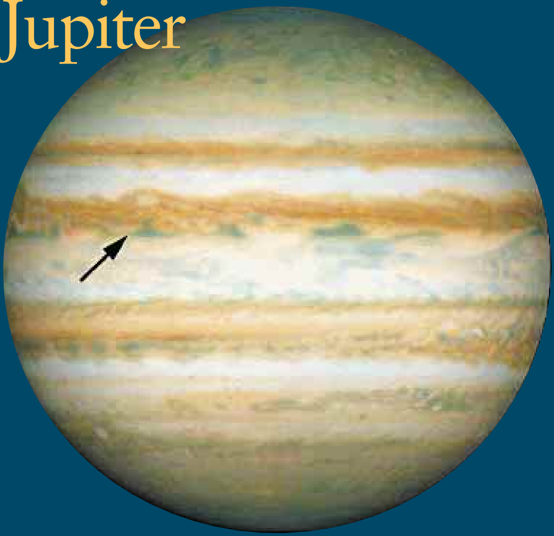
WRACKED BY EIGHTY VOLCANOES, the surface of Io makes Earth look geologically inert by comparison. The yellow, brown and red patches on this false-color mosaic (*main image*) represent different sulfur-based minerals—in other words, brimstone. A sulfur dioxide frost coats the white areas. Gas and dust have been swept into orbit, as is evident when the sun illuminates Io from the side (*inset at right*). Much of the yellowish glow comes from sodium gas. The burst of white light is sunlight scattered by the plume of the volcano Prometheus.





NASA/JET PROPULSION LABORATORY (*main image* and *inset*);
JARED SCHNEIDMAN DESIGN (*Galileo*)

The Gas Giant
Jupiter



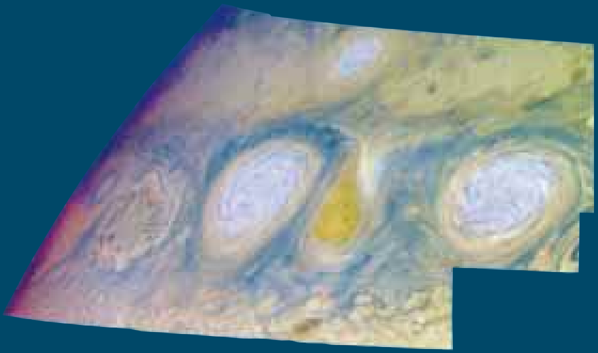
RETA BEEBE *New Mexico State University* AND NASA

Until the Galileo mission, no object touched by human hands had ever made contact with a gas giant planet. The spacecraft dropped a probe into the atmosphere just north of the equator, a location shown on this Hubble Space Telescope image taken after the probe had been targeted (*left*). The probe descended for more than an hour, measuring the composition (*table below*) before succumbing to the increasing temperature and pressure (*sequence at right*). The primordial solar composition is assumed to be the same as that of the outer layers of the sun.

CHEMICAL COMPOSITION OF UPPER ATMOSPHERE
(Number of atoms per atom of hydrogen)

ELEMENT	CHEMICAL FORM	JUPITER	SATURN	SUN
HELIUM	HELIUM	0.078	0.070 ± 0.015	0.097
CARBON	METHANE	1.0×10^{-3}	2×10^{-3}	3.6×10^{-4}
NITROGEN	AMMONIA	4.0×10^{-4}	$3 \pm 1 \times 10^{-4}$	1.1×10^{-4}
OXYGEN	WATER	3.0×10^{-4}	unmeasured	8.5×10^{-4}
SULFUR	HYDROGEN SULFIDE	4.0×10^{-5}	unmeasured	1.6×10^{-5}
DEUTERIUM	DEUTERIUM	3×10^{-5}	3×10^{-5}	3.0×10^{-5}
NEON	NEON	1.1×10^{-5}	unmeasured	1.1×10^{-4}
ARGON	ARGON	7.5×10^{-6}	unmeasured	3.0×10^{-6}
KRYPTON	KRYPTON	2.5×10^{-9}	unmeasured	9.2×10^{-10}
XENON	XENON	1.1×10^{-10}	unmeasured	4.4×10^{-11}

SOURCES: SUSHIL K. ATREYA *University of Michigan*; HASSO B. NIEMANN *NASA Goddard Space Flight Center* AND COLLEAGUES



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OVAL CLOUDS were seen by Galileo in early 1997. They have trapped a pear-shaped region between them. The ovals rotate counterclockwise; the pear-shaped region, clockwise. On this false-color mosaic of three near-infrared images, bluish clouds are thin, white ones are thick, and reddish ones are deep. A year later the ovals merged together—a vivid example of Jupiter's dynamic weather. Each oval is about 9,000 kilometers across.

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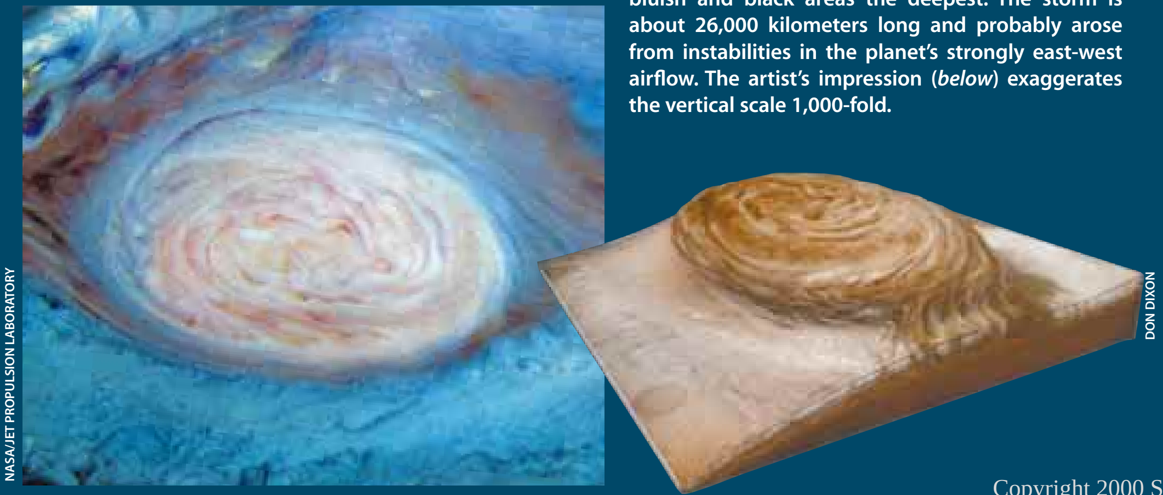
HOLE IN THE UPPER CLOUD DECK reveals the comparatively warm regions deeper down. As on other near-infrared images, bluish clouds are thin, white ones are thick, and reddish ones are deep (*diagram at right*). The Galileo probe entered just such an area, known as a hot spot. This image depicts an area 34,000 kilometers across.

GREAT RED SPOT is a vast storm system that towers some 30 kilometers above the surrounding clouds (*left*). From red to green to blue, the color coding is decreasingly sensitive to the amount of methane along the line of sight. Consequently, the pink and white areas are highest, and bluish and black areas the deepest. The storm is about 26,000 kilometers long and probably arose from instabilities in the planet's strongly east-west airflow. The artist's impression (*below*) exaggerates the vertical scale 1,000-fold.



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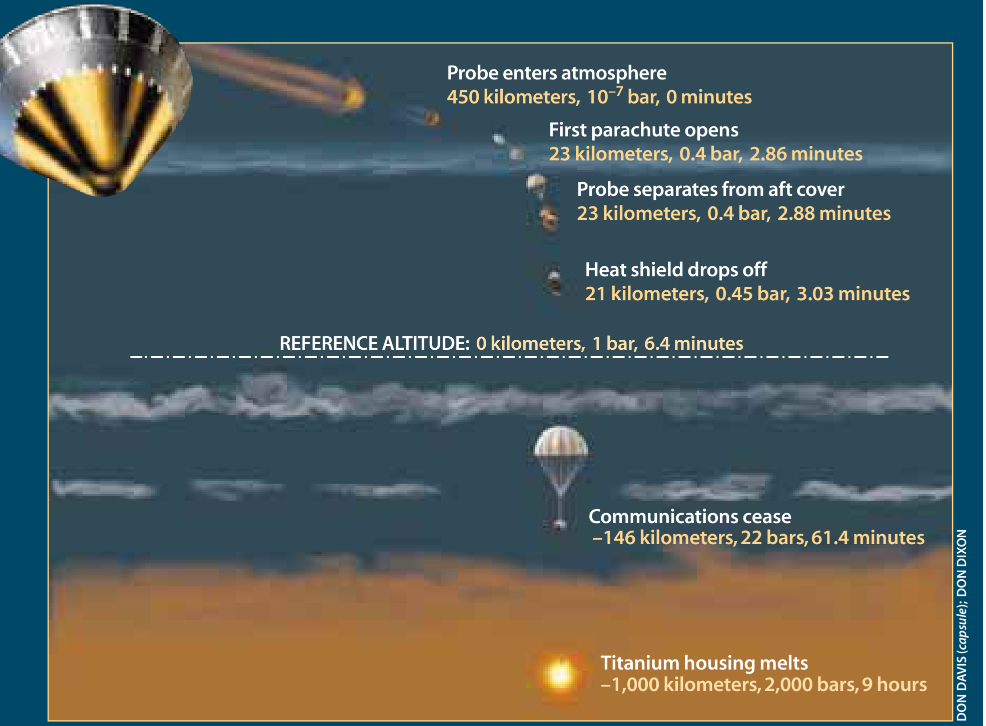
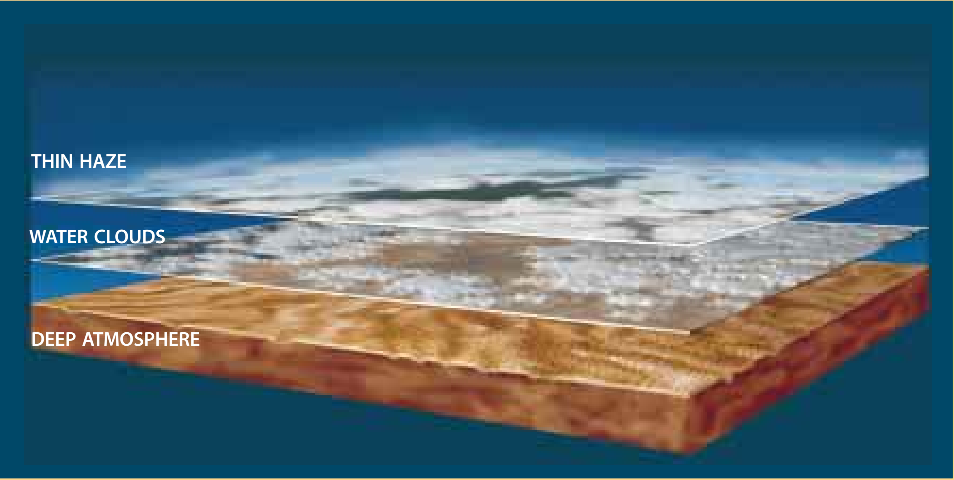
DON DIXON

LIGHTNING FLASHES appear in these orbiter images of the night side of Jupiter. Moonlight from Io dimly illuminates the ammonia cloud deck. The flashes probably originate from water clouds 100 kilometers deeper. Lightning strikes at about the same rate as in thunderstorms on Earth but 1,000 times more brightly. Each image shows an area roughly 60,000 kilometers square.



DON DAVIS (*capsule*); DON DIXON



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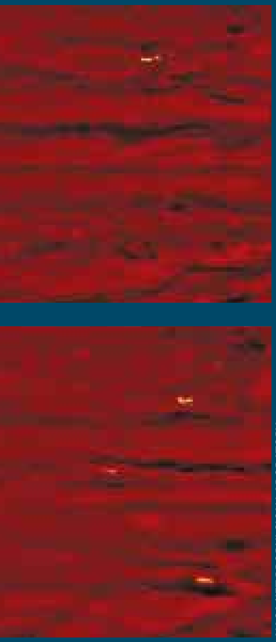

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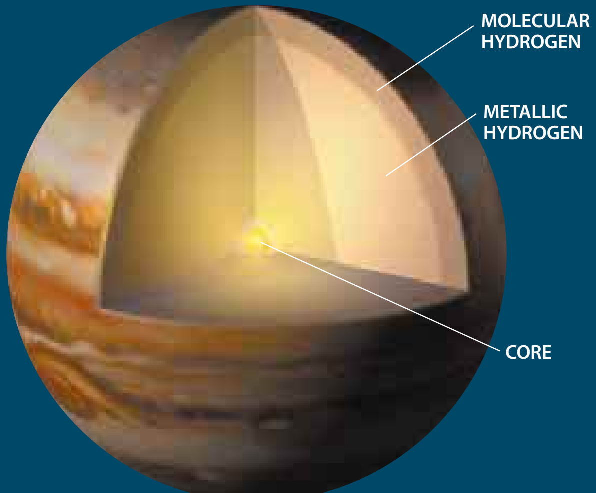
INTERIOR OF JUPITER shows that the term "gas giant" is something of a misnomer. The bulk of the planet consists of hydrogen under such immense pressures that it has become liquid and metallic. Underneath it all is a core of rock around which the hydrogen accumulated.



ALFRED T. KAMAJIAN

When engineers received the "golden bit" confirming that the probe was still alive, cheers went up in the control room and the tension began to ease. But the team still had to wait out the next two hours for the second critical event: insertion of the companion spacecraft into orbit. To slow it from interplanetary cruise enough for Jupiter's gravity to capture it, engineers instructed the German-built main engine to fire for 45 minutes. Finally, word came through that this maneuver had succeeded. The orbiter had become the first known artificial satellite of the giant planet.

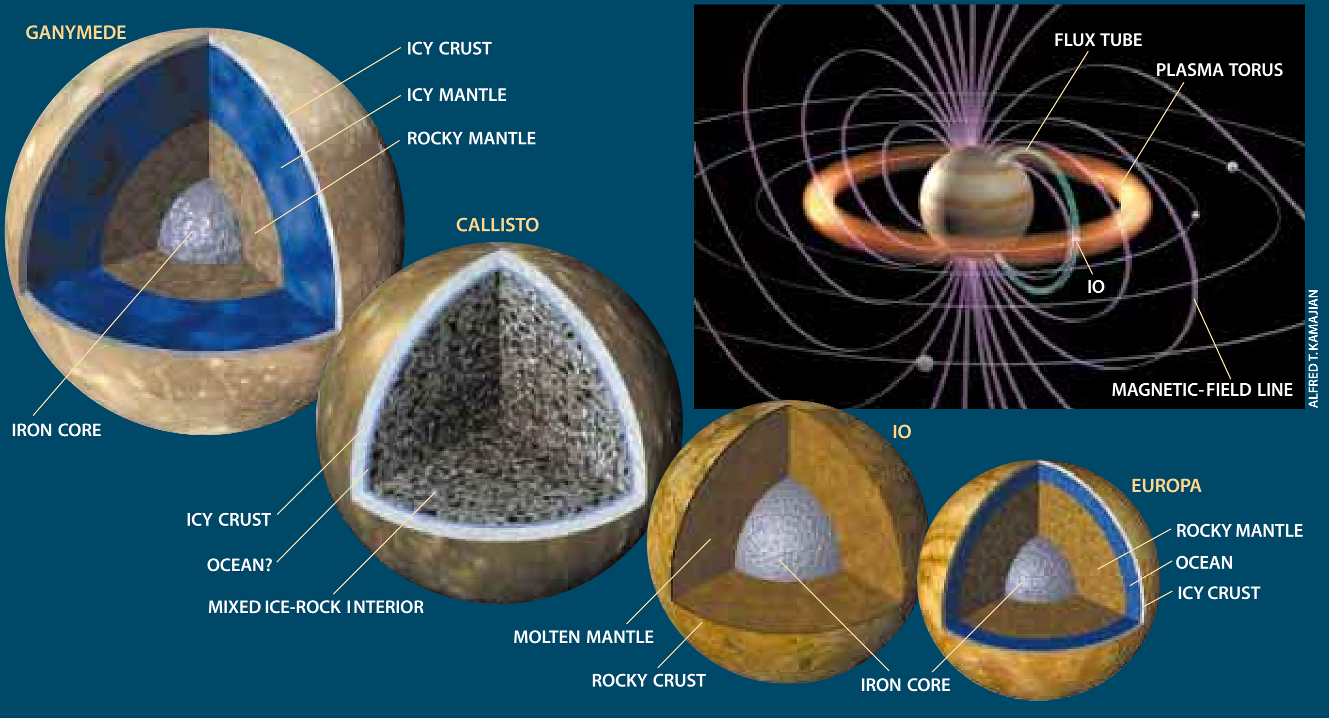
Since that day in December 1995, a mission that once seemed doomed has given researchers their first detailed view of the Jovian system, revealed only fleetingly in the Pioneer and Voyager flybys of the 1970s. The atmospheric probe penetrated the kaleidoscopic clouds and conducted the first in situ sampling of an outer planet's atmosphere, transmitting data for an hour before it was lost in the gaseous depths. The orbiter is still going strong. It has photographed and analyzed the planet, its rings and its diverse moons. Most famously, it has bolstered the case that an ocean of liquid water lurks inside Europa, one of the four natural satellites discovered by Galileo Galilei in 1610 [see "The Hidden Ocean of Europa," by Robert T. Pappalardo, James W. Head and Ronald Greeley; SCIENTIFIC AMERICAN, October 1999]. But the other large moons have revealed surprises of their own: beams of electrons that connect Io, the most volcanically tormented body in the solar system, to Jupiter; a magnetic field generated within Ganymede, the first such field ever discovered on a moon; and the subtle mysteries of Callisto, including signs that it, too, has an ocean.

The Mother of All Downdrafts

According to modern theories of planet formation, Jupiter and the other giant planets emerged from the primordial solar nebula in two stages. First, icy planetesimals—essentially large comets that had condensed out of the cloud of gas and dust—clumped together. Then, as the protoplanet grew to a certain critical size, it swept up gas directly from the nebula. Jupiter thus started off with a sample of the raw material of the solar system, which had roughly the same composition as the early sun. Since then, the planet has been shaped by processes such as internal differentiation and the

The Interiors and Magnetic Fields of
Galilean Satellites

The four Galilean satellites of Jupiter do not really deserve to be called "moons." In many ways, they are planets in their own right. The inner two, Io and Europa, are about the size and density of Earth's moon. The outer two, Ganymede and Callisto, are about the size of Mercury but much less dense. Although Galileo did not land on or dig into them, it inferred their interior structure from their gravitational forces and magnetic fields. Of the four, only Callisto does not seem to have differentiated into distinct layers of metal, rock and water ice. Jupiter's electromagnetic fields interact with all four, but especially with Io (*diagram below*). The fields scoop up ionized gases from Io's volcanic eruptions, creating a torus of plasma. A flux tube between the planet and moons carries an electric current of five million amperes. (On this diagram, the planet and moons are not to scale.)



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continuing infall of cometary material. Disentangling these processes was the main goal of the atmospheric probe.

Perhaps the most mysterious discovery by the probe involved the so-called condensable species, including elements such as nitrogen, sulfur, oxygen and carbon. Scientists have long known that Jupiter has about three times as much carbon (in the form of methane gas) as the sun. The other species (in the form of ammonia, ammonia sulfides and water) are thought to condense and form cloud layers at various depths. Impurities in the cloud droplets, possibly sulfur or phosphorus, give each layer a distinctive color. The probe was designed to descend below the lowest expected cloud deck, believed to be a water cloud at about 5 to 10 atmospheres of pressure—some 100 kilometers below the upper ammonia ice clouds. The expected weather report was windy, cloudy, hot and humid.

Yet the instruments saw almost no evidence for clouds, detecting only light hazes at a pressure level of 1.6 atmospheres. The water and sulfur abundances were low. The lightning detector—basically an AM radio that listened for bursts of static—registered only faint discharges. In short, the weather was clear and dry. So what had gone wrong with the prediction? One piece of the answer came quickly. Infrared images from Earth-based telescopes discovered that the probe had unwittingly hit a special type of atmospheric region known as a five-micron hot spot—a clearing where infrared radiation from lower, hotter levels leaks out. Jupiter has many such regions, and they continually change, so the probe could not be targeted to either hit or avoid them.

The luck (both good and bad) of descending in a hot spot did not entirely solve the mystery, however. Scientists had expected that even in these regions the gases at the depths the probe reached would match the average composition of the whole atmosphere. If so, Jupiter has an anomalously low amount of such elements as oxygen and sulfur. But no one has proposed a process that would eliminate these elements so efficiently. The other possibility is that the composition of the hot spot differs from the average, perhaps because of a massive downdraft of cold, dry gas from the upper atmosphere.

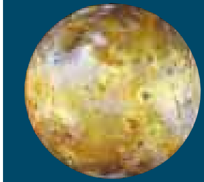
The latter theory has its own difficulties but currently seems the more likely interpretation. Just before the probe ceased transmitting, concentrations of water, ammonia and hydrogen sulfide were beginning to rise rapidly—just as if the probe was approaching the base of a downdraft. Orbiter images of another prominent hot spot show that winds converge on the center of the hot spot from all directions [*see illustration on page 42*]. The only place the gas can go is down. Orbiter spectra showed that the abundance of water and ammonia varies by a factor of 100 among different hot spots, supporting the idea that local meteorological conditions dictate the detailed composition of the atmosphere.

The one part of the weather prediction that proved correct was "windy." Jupiter's cloud bands are associated with high-velocity jet streams: westerlies and easterlies that blow steadily at several hundred kilometers per hour. On Earth the analogous winds die off near the surface. On Jupiter there is no surface; the wind profile depends on which energy source dominates the atmosphere. If a source of internal energy (such as slow contraction under the force of gravity) dominates, the winds should stay strong or increase with depth. The opposite is true if external energy (such as sunlight) is the main contributor. By tracking the probe's radio signal, scientists ascertained that winds at first increase rapidly with depth and then remain constant—indicating that Jupiter's atmosphere is driven by internal energy.

Onto Each Planet Some Rain Must Fall

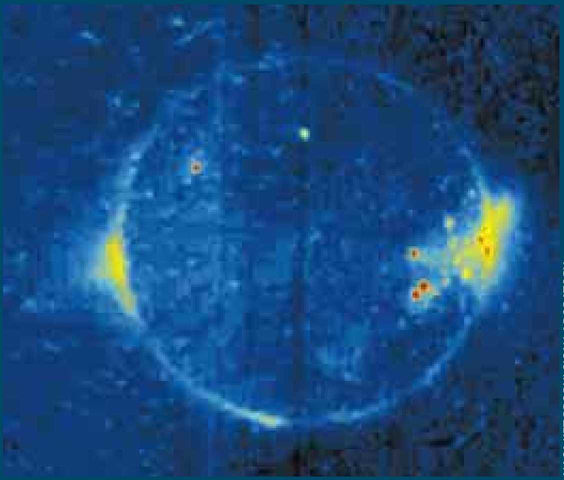
Although the probe detected only weak hints of lightning, the orbiter saw bright flashes illuminating the clouds in what are obviously massive thunderstorms [*see illustration on page* 42]. Like Voyager, Galileo found that lightning was concentrated in just a few zones of latitude. These zones are regions of anticyclonic shear: the winds change speed abruptly going from north to south, creating turbulent, stormy conditions. As on Earth, lightning may occur in water clouds where partially frozen ice granules rise and fall in the turbulence, causing positive and negative charges to separate. How deep the lightning occurs can be estimated from the size of the illuminated spot on the clouds; the bigger the spot, the deeper the discharge. Galileo deduced that the lightning is indeed originating from layers in the atmosphere where water clouds are expected to form.

For all its pains, the probe descended less than 0.1 percent of the way to the center of the planet before succumbing to the high pressures and temperatures. Nevertheless, some of its measurements hint at what happens deeper down. The concentrations of noble gases—helium (the second most abundant element in Jupiter, after hydrogen), neon, argon, krypton and xenon—are particularly instructive. Because these gases do not react chemically with other elements, they are comparatively unambiguous tracers of physical conditions within the planet. So informative is the concentration of helium that the Galileo at-



The Infernal Moon

Io



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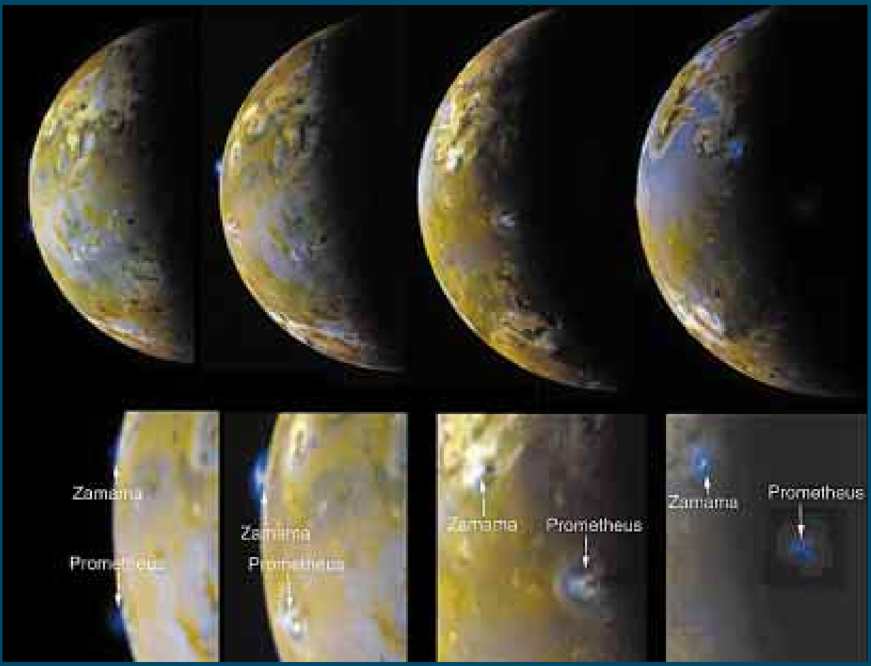
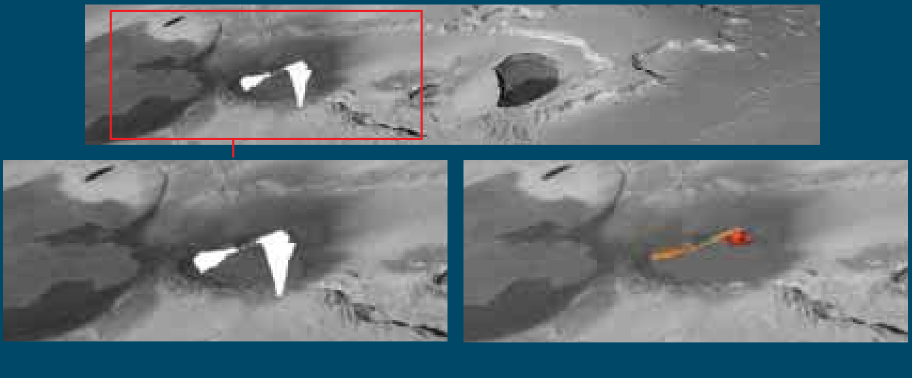
A yummy pizza color distinguished Io in the Voyager images two decades ago. Galileo's greater range of wavelengths permits even more spectacular false-color views. When the satellite is in Jupiter's shadow (*top*), lava flows become evident as small red and yellow spots. Volcanic plumes show up as glows along the edge; the one on the left is from the volcano Prometheus. A sequence of four enhanced-color images (*middle*) shows Prometheus and Zamama coming into view—first the plumes, then the volcanoes themselves, surrounded by rings of debris more than 100 kilometers in diameter. Last November, Galileo captured a huge volcanic complex in Io's northern climes (*bottom*). The image shows several craters and a massive curtain of fire. The fresh lava is glowing so brightly it overexposes the CCD camera.





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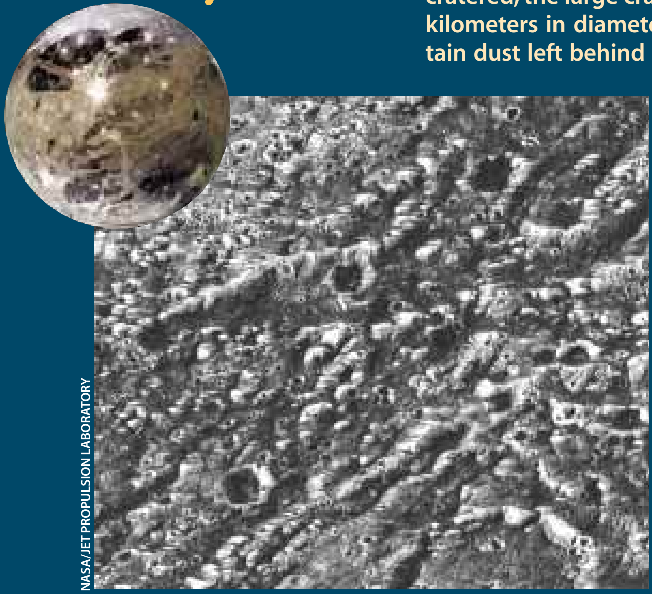
The Ice-Laced Moon of Ganymede

The largest satellite in the solar system is a strange quilt of dark and bright terrains. The dark regions, like Galileo Regio (*left*), are heavily cratered; the large crater in the foreground is 19 kilometers in diameter. Deep furrows may contain dust left behind after water ice sublimated away. The bright regions, like Uruk Sulcus (*below*), have fewer craters and more tectonic features such as grooves. This image depicts an area roughly 400 kilometers square. Some regions, like Tiamat Sulcus (*right*), shown here just after sunrise, contain both types of terrain.



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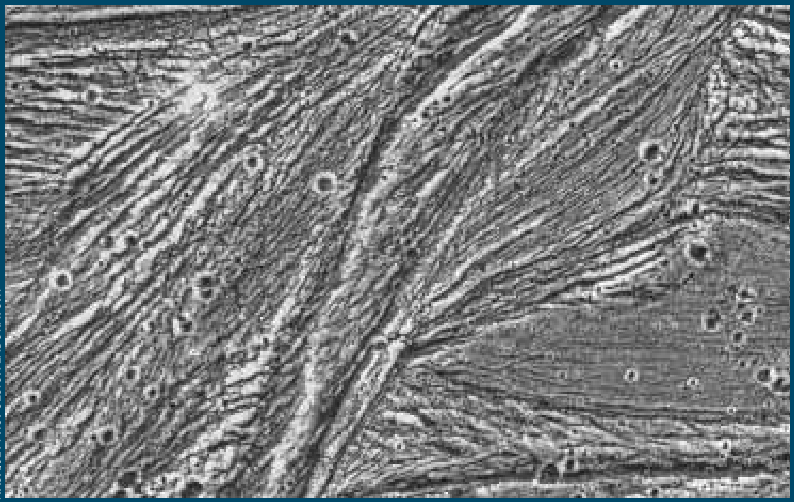

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mospheric probe carried an instrument dedicated solely to its measurement.

Infrared spectra obtained by Voyager suggested that Jupiter contains proportionately much less helium than the sun does, an indication that something must have drained this element from the upper atmosphere. Galileo, however, found that Jupiter has nearly the same helium content as the outer layers of the sun [*see table on page 42*]. This result still requires that some process remove helium from the Jovian atmosphere, because the outer layers of the sun have themselves lost helium. But that process must have started later in the planet's history than researchers had thought. Galileo also discovered that the concentration of neon is a tenth of its solar value.

Both these results support the once controversial hypothesis that the deep interior of Jupiter is deluged with helium rain. There helium becomes immisible in the hydrogen-rich atmosphere, which at high pressures—millions of times sea-level pressure on Earth—is perhaps better thought of as an ocean. Being heavier, the helium gradually settles toward the center of the planet. Under certain conditions, neon dissolves in the helium raindrops. Helium may also precipitate out on Saturn, whose helium depletion may be even more extreme.

After several years of analysis, researchers recently announced the abundance of the other noble gases. Argon, krypton and xenon are enriched compared with the solar composition by about the same factor as carbon and sulfur. That, too, is a mystery. The only way to trap the inferred quantities of these gases is to freeze them—which is not possible at Jupiter's current distance from the sun. Therefore, much of the material that makes up the planet must have come from colder, more distant regions. Jupiter itself may even have formed farther from the sun, then drifted inward [see "Migrating Planets," by Renu Malhotra; Scientific American, September 1999].

A final clue to Jovian history came from the measurement of deuterium, one of the heavy isotopes of hydrogen. The concentration is similar to that on the sun and is distinctly different from that of comets or of Earth's oceans. The finding suggests that comets have not had a major effect on the composition of Jupiter's atmosphere, despite the spectacular effects when they hit, as demonstrated during the Shoemaker-Levy 9 collisions in 1994.

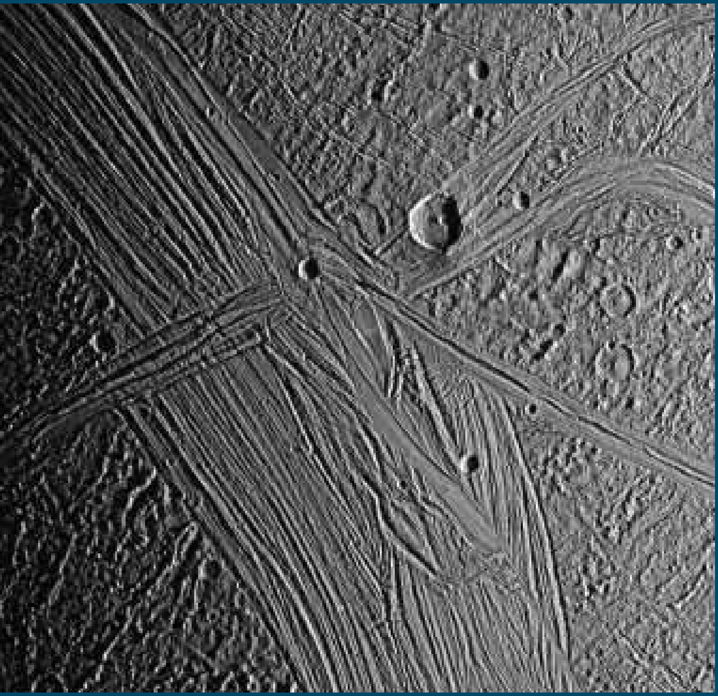
World of Fire

After the orbiter relayed the probe data to Earth, it commenced its tour of the Jovian system—to date, a total of 26 orbits of the planet, with multiple flybys of each of the four Galilean satellites. The limelight has been on Europa, whose surface geology and other features point to the existence of a liquid ocean beneath the ice sometime in Europa's history, probably in the geologically recent past. But the other moons have not been neglected.

The innermost Galilean satellite, Io, stole the show during the two Voyager encounters. The initial pictures from those spacecraft showed a remarkably young surface, the only one in the solar system with essentially no impact craters. Later, images taken for navigation purposes serendipitously caught immense eruptive plumes. Subsequent observations confirmed that Io is wracked by volcanic activity. The size of Earth's moon, it spews 100 times more lava than Earth does [see "Io," by Torrence V. Johnson and Laurence A. Soderblom; Scientific American, December 1983].

Galileo has spent less time looking at Io than at the other moons, primarily because of the danger to the spacecraft: Io lies deep in Jupiter's intense radiation belts. Galileo flew within 900 kilometers of Io's surface just before the orbit insertion in 1995 but did not revisit until last October, when the bulk of its mission had been completed and scientists felt free to take more risks. Although concerns about the jam-prone tape recorder forced cancellation of imaging and spectroscopy during the 1995 flyby, the particle detector and magnetometer remained active.

They found that the empty space around Io is anything but. It seethes with subatomic particles blasted out by volcanic eruptions and stirred up by Jupiter's magnetic field. Electron beams course down the field lines that connect



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Artist's impression of the surface

DON DAVIS

Io to Jupiter's atmosphere; dense, cold plasmas permeate the wake left behind Io by the magnetic field sweeping by. Whenever Io passed through Jupiter's shadow, Galileo saw the moon outlined by a thin ring of glowing gas, lit up by the impact of electrons from the Jovian magnetosphere. In short, Io is tightly linked to the giant planet by what amounts to the largest electric circuit in the solar system [*see illustration on page 44*].

For most of its mission Galileo studied the tortured surface of Io from a safe distance. Based on how brightly the volcanoes glow at different visible and near-infrared wavelengths, it inferred their temperature, a measurement critical to determining the composition of the lavas. Most volcanoes on Earth disgorge lava of basaltic composition—iron, magnesium and calcium silicates rich in the minerals olivine and pyroxene. Basaltic melts typically have temperatures ranging from 1,300 to 1,450 kelvins (1,050 to 1,200 degrees Celsius). In contrast, telescopic observations of Io several years ago suggested temperatures of 1,500 to 1,800 kelvins. These temperatures ruled out substances that melt at lower temperatures, such as liquid sulfur, which had been suggested previously as a dominant volcanic fluid on Io.

When Galileo's measurements came down, the enigma intensified. Lavas on the moon are actually 1,700 to 2,000 kelvins. Magma this hot has not been common on Earth for more than three billion years. Io may thus be giving scientists an unexpected glimpse into Earth's geologic youth, a time when its interior temperatures were higher and the composition of the upper mantle different from today's.

When Galileo finally returned to Io last fall, the mission team was uncertain whether the spacecraft would survive the radiation. On one of its passes, it autonomously aborted the data-taking sequence just four hours before reaching Io, and the team rebooted with only minutes to spare. Several instruments also suffered damage, but all continued to work and in the end returned spectacular data. Io's active volcanoes were finally captured up close and personal [*see illustration on page 45*].

In a Field of Its Own

One of Galileo's major discoveries was made during its very first orbital encounter—with Ganymede, Jupiter's largest moon. About half an hour before the spacecraft reached its closest approach, the radio-noise instrument, designed to record ambient electrical fields, began to go haywire. The relatively quiet background radio signals seen throughout most of the Jovian system changed abruptly to a complex, active radio spectrum. For 45 minutes the activity remained intense, and then it ceased as suddenly as it had begun. When the radio noise commenced, the magnetometer readings shot up fivefold.

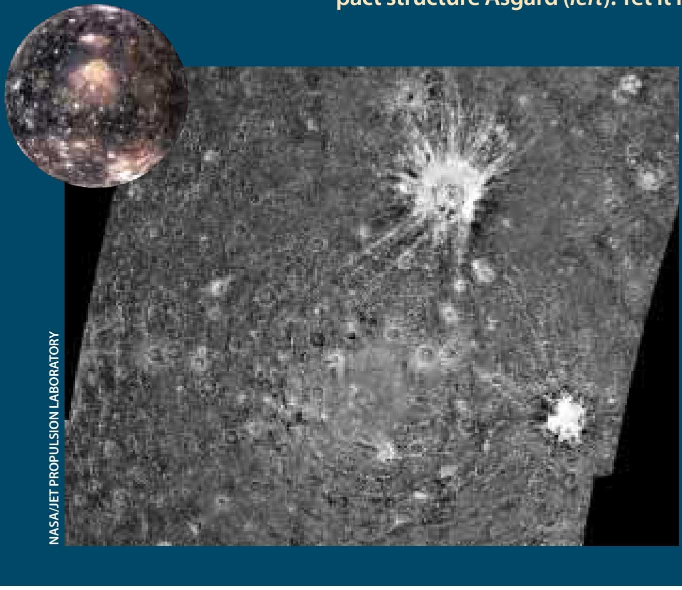
Plasma researchers had seen signatures of this sort before, when spacecraft carrying similar instruments entered and exited magnetospheres at Earth, Jupiter, Saturn, Uranus and Neptune. Two subsequent Ganymede flybys confirmed their suspicions: the moon is magnetized, generating a dipole field similar to those of these planets. No other satellite has such a field. Earth's moon and Mars may have had fields in the past, but currently they exhibit only limited patches of magnetic variation that represent magnetized rocks on the surface. Like a set of nested Russian dolls, Ganymede has a magnetosphere contained within Jupiter's huge magnetic domain, which in turn is embedded in the sun's.

Tracking of the spacecraft signal allowed researchers to probe Ganymede's gravity field and therefore its internal structure. They concluded that it probably has a dense core about 1,500 kilometers in radius with a surrounding icy mantle 700 kilometers deep. Geochemical models suggest that the core consists of a sphere of iron or iron sulfide enveloped in rock. The inner metallic core could produce the dipolar magnetic field.

Yet theorists are not sure quite how. Although scientists compare planetary magnetic fields to bar magnets, the analogy can be misleading. Solid iron at the center of a planet or large moon would be too hot to retain a permanent magnetic field. Instead a magnetic field is thought to involve a convecting, conductive liquid. Models of Ganymede indicate that its interior can easily become

Pockmarked Callisto

This most baffling of the Galilean satellites is densely packed with large craters, such as the massive, multiringed impact structure Asgard (*left*). Yet it is comparatively free of small craters, and those that do exist are fuzzy (*below* and *right*)—suggesting that dusty material has somehow flowed across the surface.



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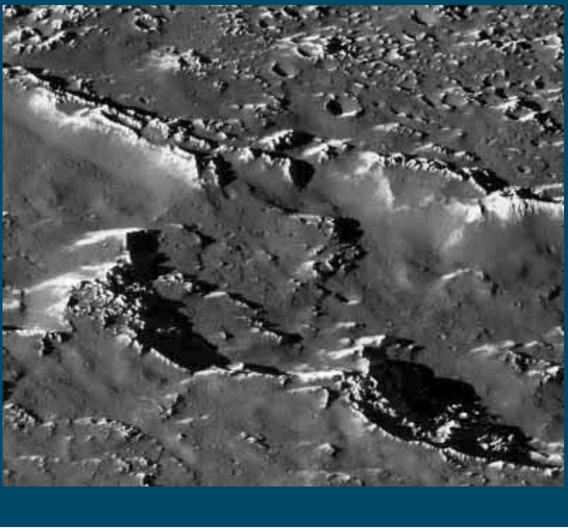

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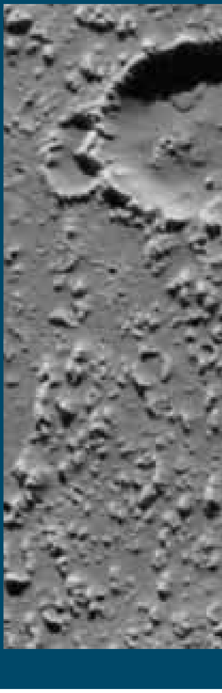


hot enough to melt iron or iron sulfide. But the same models show that convection will cease as the core gradually cools; the conditions required for convection should last only a billion years or so.

The answer may lie in the orbital resonance of the inner three Galilean satellites. Io goes around Jupiter precisely four times for each time Europa completes two circuits and Ganymede one. Like pushing a child's swing in time with its natural pendulum period, this congruence allows small forces to accumulate into large outcomes—in this case, distorting the orbits from their default circular shape into more oblong ellipses. The effect on the moons is profound. Because the distance between them and Jupiter is continuously changing, the influence of Jupiter's gravity waxes and wanes, stretching the moons by an ever varying amount. The process, known as tidal heating, drives the volcanism on Io and keeps Europa's putative ocean from freezing.

Researchers used to think that tidal heating was of little consequence for Ganymede, the outermost of these three moons. But now they realize that the orbits may have shifted over time. Consequently, the resonances may once have been stronger and Ganymede's orbit more perturbed than it is now. The immense fault systems that wind across the surface may record this earlier period of intense heating. If so, the moon is still cooling off, and its core can continue to generate a magnetic field.

Compared with flamboyant Europa, Io and Ganymede, the outermost Galilean satellite, Callisto, was always thought rather drab. In Voyager images it epitomized the traditional stereotype for icy satellites: an old, frozen, pockmarked mudball. But Galileo observations tell a different story.

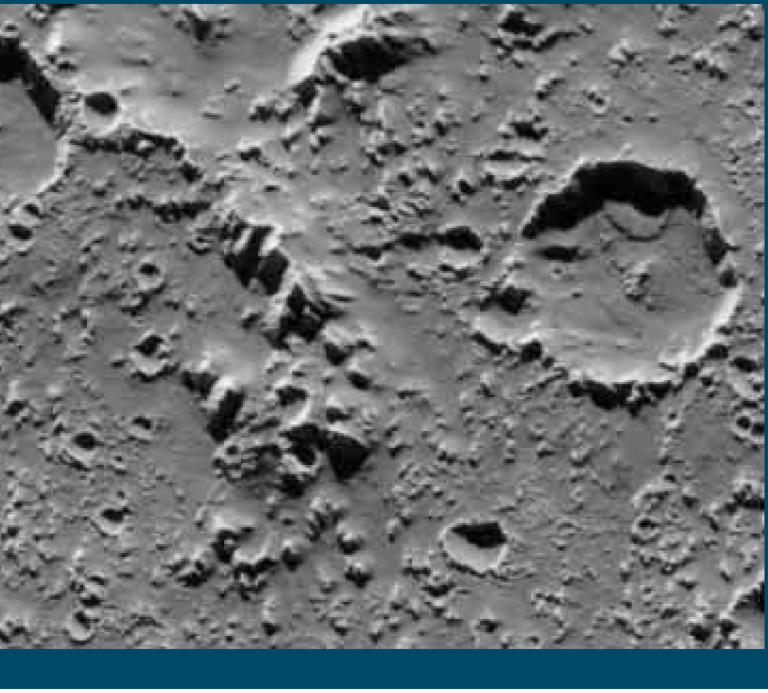
Old but Hardly Dull

Callisto is covered with large impact scars, ranging from craters kilometers in diameter to the so-called palimpsest named Valhalla, some 1,500 kilometers across. The surface is believed to date back more than four billion years to the rain of meteoritic and cometary debris left after the formation of the planets and satellites. In this sense, Callisto is indeed old. Seen close-up, however, Callisto's surface is blanketed by fine, dark debris. Small craters, which on most other bodies are produced in abundance, are largely absent. Surface features appear softened and eroded. Clearly, some young processes have been at work. Among the ideas proposed have been electrostatic levitation of fine dust, which would allow it to "flow" across the surface, and evaporation of ices from the surface, which would leave behind deposits of darker, less volatile material. So far none of the explanations is satisfying.

Intriguingly, near-infrared spectra show not only water ice and hydrated minerals, as expected, but also four unusual absorption features near a wavelength of four microns. One appears to be carbon dioxide trapped in the surface, perhaps as inclusions in icy particles or bubbles produced by radiation damage to the surface. Two other spectral features probably represent sulfur in the surface, which may originate in Io's volcanic eruptions. The fourth spectral feature is the strangest. Its wavelength corresponds to that absorbed by carbon-nitrogen bonds. In fact, laboratory spectra of complex organic molecules called tholins by the late Carl Sagan are similar. Tholins are thought to resemble organic material in the solar nebula; clouds of interstellar ice grains have comparable spectra. Taken together, the data provide the first direct evidence that icy satellites contain the carbon, nitrogen and sulfur compounds common in primitive meteorites and comets. These materials are also some of the most important for life.

The internal structure of Callisto shows the same paradoxical dichotomy between age and youth that the surface exhibits. Unlike the other Galilean satellites, Callisto seems more like a uniformly dense sphere, indicating that most of its rock and ice are mixed together. A core is ruled out. Therefore, the interior has never been heated strongly, either by radioactive decay or by tides. The moon does not participate in the orbital resonance that kneads the other Galilean satellites.

On the other hand, the moon is far from dead. As the Galileo magnetometer found, Callisto seems to perturb the surrounding Jovian magnetic field in a



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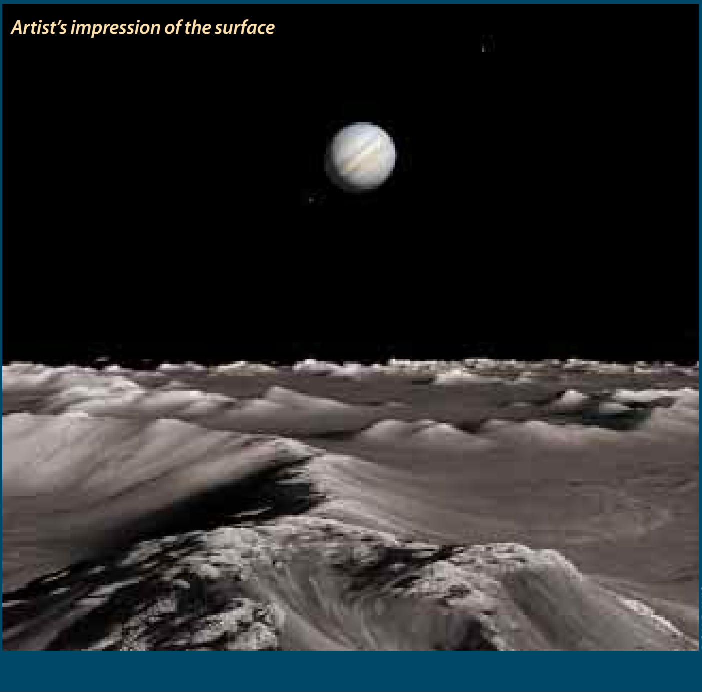

Artist's impression of the surface

DON DAVIS

peculiar pattern. This disturbance, unlike Ganymede's, resembles what is seen in classic physics experiments in which a hollow copper sphere is subjected to a changing magnetic field. In such an experiment, electric currents are set up in the conducting shell of the sphere, which in turn produces a magnetic field that exactly counters the imposed field. Callisto's field seems to be induced in much the same way.

But what could form the electrically conducting layer? Rock, ice and ionospheric particles are poor conductors. Researchers are left with a possibility that not long ago seemed outrageous: salty ocean water. Seawater is a weak conductor with the right properties to explain the readings. A global liquid layer some tens of kilometers thick could produce the observed signature. The combination of evidence for a comparatively undifferentiated interior and for a global ocean presents a severe challenge for theorists. Somehow Callisto must be hot enough to support an ocean but not so hot that light and heavy materials separate. The water layer might be sandwiched between a radioactively heated interior, where convection keeps the material mixed, and a thin icy shell, where a different convection cycle cools the ocean. So much for dull old Callisto.

Although much of Galileo's mission involved studies of the Galilean moons, the orbiter did not overlook the smaller members of Jupiter's family. Its camera captured each of the four inner, small moons—Metis, Adrastea, Amalthea and Thebe, in order of distance from Jupiter. A major finding was that these small moons are directly responsible for Jupiter's rings. A special series of pictures was taken while the spacecraft was within Jupiter's shadow, allowing the sun to backlight the tiny dust particles that make up the rings. These pictures not only show the main rings and the tenuous gossamer ring seen by Voyager in 1979, but also reveal for the first time the complex structure of the gossamer ring. It consists of multiple layers directly related to the orbits of Amalthea and Thebe. Thus, the rings are probably microscopic debris kicked off the moons by the impact of tiny metoroids. [*Editors' note: An upcoming article will examine the rings in greater detail.*]

The data gathered by Galileo have revolutionized scientists' view of Jupiter and its moons, which we have come to recognize as a kind of planetary system comparable in complexity to the solar system itself. The Voyager flybys provided the adrenaline rush of seeing worlds for the first time, but only an intensive investigation such as Galileo's could have revealed the nuances and the limitations of seemingly straightforward categories such as "thundercloud" and "icy satellite." Soon it will be Saturn's turn to enter this new phase of exploration. Another two-in-one spacecraft—Cassini-Huygens—arrives there in 2004. It, too, will probably raise more questions than it answers. SA

The Author

TORRENCE V. JOHNSON has an asteroid named after him: 2614 Torrence, a body about one kilometer in diameter. Working at the Jet Propulsion Laboratory in Pasadena, Calif., he has been the project scientist for Galileo since 1977—some three quarters of his career as a planetary scientist. He was a member of the imaging team for Voyager and is now on the imaging team for the Cassini mission to Saturn.

Further Information

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