



A Look at the Galilean Satellites After the *Galileo* Mission

From volcanic eruptions hotter than those typically found on Earth to ocean sandwiches with water trapped between ice layers, the *Galileo* mission revealed fascinating phenomena on Jupiter's four largest moons.

Torrence V. Johnson

During its nearly eight-year mission from December 1995 to September 2003, *Galileo* transformed our view of the Jovian system. The stage for *Galileo*'s show was set more than 20 years ago. When the two *Voyager* spacecraft sped by Jupiter in 1979, they sent back data that made instant scientific celebrities of the giant planet's four big moons. Io, Europa, Ganymede, and Callisto, known collectively as the Galilean satellites, had been tied to many key milestones in physics and astronomy since their discovery by Galileo in 1610. Among the milestones were Ole Roemer's measurement of the speed of light, Pierre-Simon Laplace's mathematical investigation of resonant orbits, the determination of longitude, and Albert Michelson's development of the stellar interferometer. *Voyager*'s reconnaissance made the Galilean satellites targets for exploration on a par with the Moon, Mars, and Venus. Io's volcanoes, Callisto's cratered landscape, Ganymede's icy tectonics, and enigmatic Europa's smooth, fractured, nearly uncratered surface all raised key questions about the formation and evolution of Jupiter and its moons.

Even as the *Voyager* mission was on its way, plans were being laid to return to Jupiter's realm. In 1976, a NASA science committee led by James van Allen proposed the investigation of Jupiter, its magnetosphere, and its principal satellites as the three high priority objectives for the new mission destined to be named for Galileo. *Voyager*'s discoveries further intensified interest in the mission objectives and added a host of new questions for *Galileo* to address. What is the interior structure of the satellites? Do they have cores? Do any of the moons have intrinsic magnetic fields? What is the nature of Io's volcanism: silicate or sulfur? Do the moons have atmospheres and how do those atmospheres and the moons themselves interact with Jupiter's magnetosphere? What is the composition of the non-ice material on the moons' surfaces? Does an ocean exist beneath Europa's icy crust?

As the mission unfolded, its agenda—inspired by the *Voyager* mission—expanded as *Galileo* repeatedly observed each satellite from unprecedented ranges, sometimes skimming just a few hundred kilometers from their surfaces. Discovery followed discovery as scientists absorbed the new data and added layers of complexity to their view of the satellites. The mission ended when

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Galileo plunged into Jupiter's atmosphere, a deliberate maneuver designed to avoid the risk that the craft might crash into Europa.

Peeling the onions

In general, it is very difficult to determine the interior structure of a planet, even the one we are sitting on. One of the great triumphs of 20th-century

geoscience was the exploration of Earth's interior through worldwide seismic nets, magnetic surveys, and space geodesy. Studying the interiors of other planetary bodies is a major challenge. Earth's moon is the only one for which direct seismic data are available, thanks to seismometers left on the surface by *Apollo* astronauts. A combination of seismic data, gravity and topography, dynamic studies, and magnetic induction constrains the structure of the lunar interior.

For the Galilean satellites' interiors, models based on *Voyager*'s data were constrained only by measurements of mass and radius coupled with theoretical models of the moons' thermal histories. Assuming heating primarily by radiogenic elements, those models suggested that Ganymede and Callisto should be differentiated. Believed to be about equally composed of ice and rock, the two moons would have heavy cores of rock and iron surrounded by thick water-ice mantles. Callisto's dark, cratered surface, however, led many to suspect—despite model predictions—that it might not be differentiated. Volcanic Io, heated by tides, was assumed to be differentiated, and models of Europa ranged from cool, relatively undifferentiated structures with a thin water-ice layer to highly differentiated interiors covered with thick ice and perhaps liquid water.

Investigators proposed to provide far stronger constraints on the satellites' interiors by having *Galileo* make a series of precisely tracked, close flybys that would determine nonspherical terms in the moons' gravity fields. Spacecraft tracking had been used since the beginning of space exploration to measure the effects of gravity on trajectories. In the case of a flyby of a spherically symmetric object, the results would depend only on the total mass, not on any interior radial structure. The Galilean satellites are, however, significantly nonspherical, being distorted both by their spin and by strong tidal forces from Jupiter's gravitational field. That distortion results in triaxial shapes, flattened in the polar dimension and with a tidal bulge along the moon-Jupiter line. The magnitudes of the combined distortions depend on the radial distributions of mass inside the moons. Thus, the mass distributions in the Galilean satellites can be constrained by measuring the nonspherical terms in their gravitational fields. More precisely, one determines the J_2 and C_{22} coefficients in the harmonic expansion of the fields.

The magnitude of the nonspherical portion of the satellites' gravity can be related directly to the axial moment of

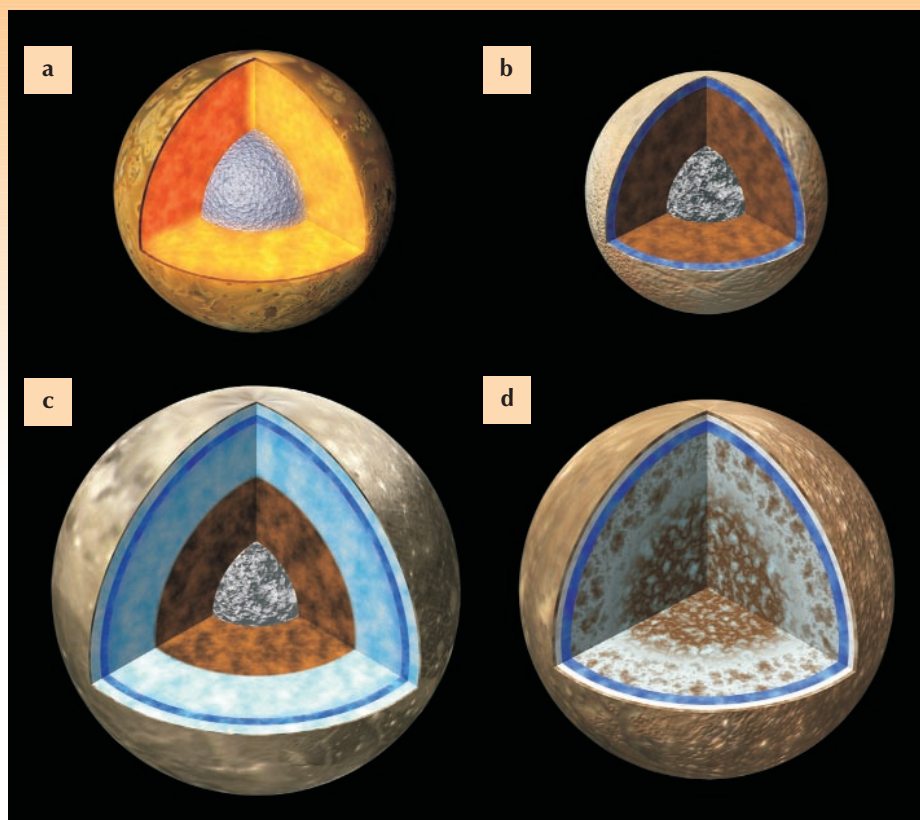


Figure 1. Internal structures of the Galilean satellites can be modeled with the help of moment-of-inertia data. (a) Io, the moon nearest to Jupiter, is highly differentiated, with a high-density core and lower-density outer regions. (b) Europa, next in order, features a layer of water or ice some 75–150 km thick over a denser region of iron and rock. (c) Ganymede, like Io, is highly differentiated. (d) Callisto, farthest from Jupiter, shows surprisingly little differentiation. (Courtesy of Zareh Gorjian and Eric De Jong, NASA/Jet Propulsion Laboratory.)

Europa's rock and iron constituents yield models with an outer layer of water or ice about 75–150 km thick overlying a denser mantle and core made of rock and iron. Figure 1 shows cutaways of the moons' internal structures.

The interior models suggest significantly different histories of thermal evolution. In addition to radionuclide heating, tidal heating is implicated in explaining

inertia if one makes the key assumption that the satellites are in overall hydrostatic equilibrium. The moment of inertia gives a more or less direct indication of the degree to which denser material is concentrated toward the center of the satellite. With the mean density of the satellite as a constraint, scientists can use typical rock, iron, and ice parameters to help construct multilayer models consistent with the derived moment of inertia.

The table below gives each satellite's J_2 and C_{22} coefficients, along with the axial moment of inertia (C) normalized to take into account the satellite's mass (M) and radius (R). Io and Ganymede both appear to be heavily differentiated with high-density inner regions and less dense material in their outer layers. Typical Io models suggest a dense iron and iron sulfide core whose radius is about half that of the satellite. Callisto, although similar to Ganymede in many respects, is surprisingly less differentiated: Models allowing for the greatest degree of differentiation suggest a relatively rock-free outer layer a few hundred kilometers thick and no large mantle or core made of rock and iron. Reasonable density values for

the characteristics of the inner three moons. The weakly differentiated state of the most distant Galilean satellite, Callisto, provides an important new constraint for post-*Galileo* models of satellite formation. While requiring that both Ganymede and Callisto form under conditions that permit the incorporation of water-ice, models must also demand slower accretion of the three ice-rock satellites to prevent early melting differentiation, and more extensive differentiation, of Callisto.

A moon with magnetism

Galileo's second close encounter with a satellite was with Ganymede, over a large dark region—appropriately dubbed Galileo Regio on *Voyager*-based maps. The encounter immediately confirmed the value of *Galileo's* ability to fly by the moons at altitudes of a few hundred kilometers, some 100–1000 times closer than *Voyager*. Data transmitted during the encounter showed sharp changes in magnetic-field and plasma-wave characteristics near the satellite. Scientists' preliminary interpretation of the data was that they indicated a dipolar magnetic field from Ganymede itself, oriented opposite to the local field from Jupiter's huge magnetic domain (see figure 2). The playback of more complete data confirmed that finding, and subsequent close encounters mapped out Ganymede's own magnetosphere in detail.¹

Ganymede's magnetic field was not completely unexpected. Indeed, the search for satellite magnetic fields was among the original *Galileo* objectives. At the time, however, considerable debate and skepticism surrounded the idea that any of the moons would have the necessary conditions to produce an intrinsic field.

Scientists have yet to provide a completely satisfactory explanation for Ganymede's magnetic field. Models for production of Earth's field by a magnetic dynamo require an electrically conducting fluid and, very important, convection of that fluid. For Ganymede, several of the necessary conditions appear to exist: Gravitational data are consistent with an iron-rich core and thermal models show

Gravity Coefficients and Normalized Moments of Inertia

	$J_2 \times 10^6$	$C_{22} \times 10^6$	C/MR^2
Io	1859.5 ± 2.7	558.8 ± 0.8	0.37824 ± 0.00022
Europa	435.5 ± 8.2	131.5 ± 2.5	0.346 ± 0.005
Ganymede	127.53 ± 2.9	38.26 ± 0.87	0.3115 ± 0.0028
Callisto	32.7 ± 0.8	10.2 ± 0.3	0.3549 ± 0.0042

Adapted from G. Schubert, J. D. Anderson, T. Spohn, W. McKinnon, in *Jupiter: The Planet, Satellites and Magnetosphere*, F. Bagenal, T. Dowling, W. McKinnon, eds., Cambridge U. Press, New York (in press).

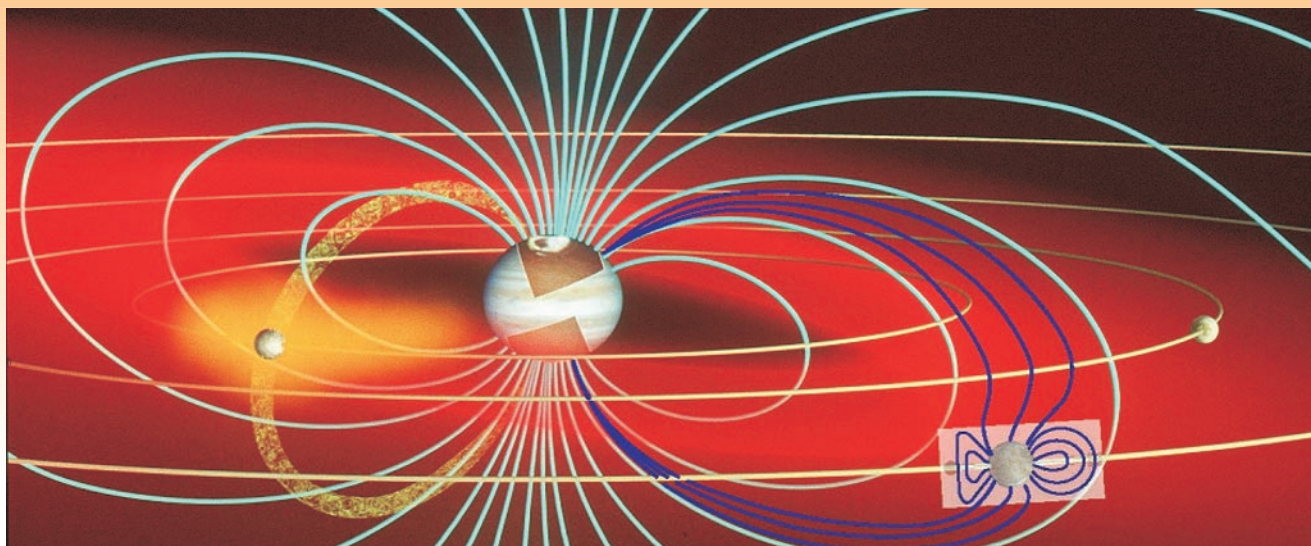


Figure 2. Ganymede's magnetic field (dark blue) is oriented opposite to the much larger local field (light blue) created by Jupiter. (Based on a graphic provided by John Spenser, Southwest Research Institute.)

that the core could have remained molten to the current epoch. But those same models allow core convection only early in Ganymede's history and suggest that magnetic-dynamo field generation would have been difficult during the past 1–2 billion years. It may be that Ganymede's interior has recently been stirred by passage through a gravitation resonance or that differentiation and core formation were delayed by 1–2 billion years. Perhaps important gaps remain in scientists' basic understanding of planetary magnetic-field generation. After all, many years after the magnetic dynamo was proposed as the source of Earth's magnetic field, major questions still exist about the structure of Earth's inner core and the processes driving field generation on our own planet.

None of the other satellites possesses a strong intrinsic field. The most probable explanation in the case of Callisto is the moon's lack of a suitable conducting and convecting core structure. For Io, with its differentiated interior and presumed iron-rich liquid core, tidal heating of the mantle may warm the core from above, inhibiting the convection needed to produce a field. Europa's lack of an intrinsic field is consistent with models of thermal history similar to those that predict no current field for Ganymede either. The absence of a field around Europa may indicate that for some reason, the moon did not experience a thermal history resulting in core convection. Tidal heating as postulated for Io is one possibility.

Hotter than Hell?

After *Voyager* discovered volcanism on Io during its first 1979 flyby, two major contending views as to the nature of the phenomenon emerged. One was a model based on liquid sulfur, the other was a more traditional model based on liquid silicate. A key difference between the two is the temperature of the volcanic fluids: Sulfur melts have relatively low temperatures below 700 K and silicate melts have temperatures greater than about 1500 K. Numerous studies performed between *Voyager*'s flybys and *Galileo*'s arrival at Jupiter supported each of the models, though telescopic observations of sporadic high-temperature outbursts showed that silicate volcanism occurs at least occasionally.

Galileo observations of Io quickly established that many eruption sites are active across the surface at any given time. Figure 3 shows an image of one such eruption. With the help of near-infrared images from the solid-state

imaging camera system (SSI) and the near-infrared mapping spectrometer (NIMS), scientists can estimate the temperatures of the eruptions. Measurements at 1- to 5- μm near-IR wavelengths, made during eclipses of Io by Jupiter and on the night side of the moon, showed many eruption sites with easily detectable glows from hot lava (see PHYSICS TODAY, February 2000, page 20). Consistent with the Planck law, the strong signals at the shorter wavelengths showed the presence of relatively hot lava. Thus, the dominant mode of volcanism on Io is the higher-temperature, liquid-silicate variety.

Moreover, temperature estimates from some eruption sites suggest that Io's lava may be hotter than that seen on Earth today. Melt temperatures of rocks depend on composition. As figure 4 illustrates, temperature estimates in some places top 1800 K, which suggests lava with a high magnesium content.² (The rocks that melt to yield such lava are called ultramafic.) On Earth, very high-temperature volcanism is recorded primarily in very old volcanic rocks—komatiites—that date back some 2.5 billion years. Thus, tidally heated, volcanic Io may be a window to Earth's hot, volcanic past.

Diffuse but important atmospheres

None of the Galilean satellites has a dense, gravitationally bound atmosphere like that observed on Saturn's large moon, Titan. In the 1970s, however, it became clear that the satellites might possess highly tenuous, dynamic atmospheres that interact with the Jovian magnetospheric environment in which they are immersed. Telescopic observations made in that decade showed atomic sodium, atomic potassium, and ionized sulfur associated with Io, and a radio occultation performed by *Pioneer 10* in 1973 detected an Ionian ionosphere. *Voyager*'s observation of active volcanism on Io and its identification of sulfur dioxide gas in Io's volcanic plumes revealed the source of some of the satellite's atmospheric constituents. Although *Voyager* detected no atmospheres around the other moons, theoretical calculations suggested that they should have low-density atmospheres produced from the sublimation and sputtering of surface ices.

Galileo's observations, together with results from the *Hubble Space Telescope (HST)*, have provided a much more detailed picture of the satellites' tenuous atmospheres and their interactions with their environment. Images of Io

Figure 3. Volcanic eruptions are common on the surface of Io. This eruption, photographed by *Galileo*, occurred on 22 February 2000 in a region called Tvashtar Catena. (Courtesy of NASA/Jet Propulsion Laboratory.)

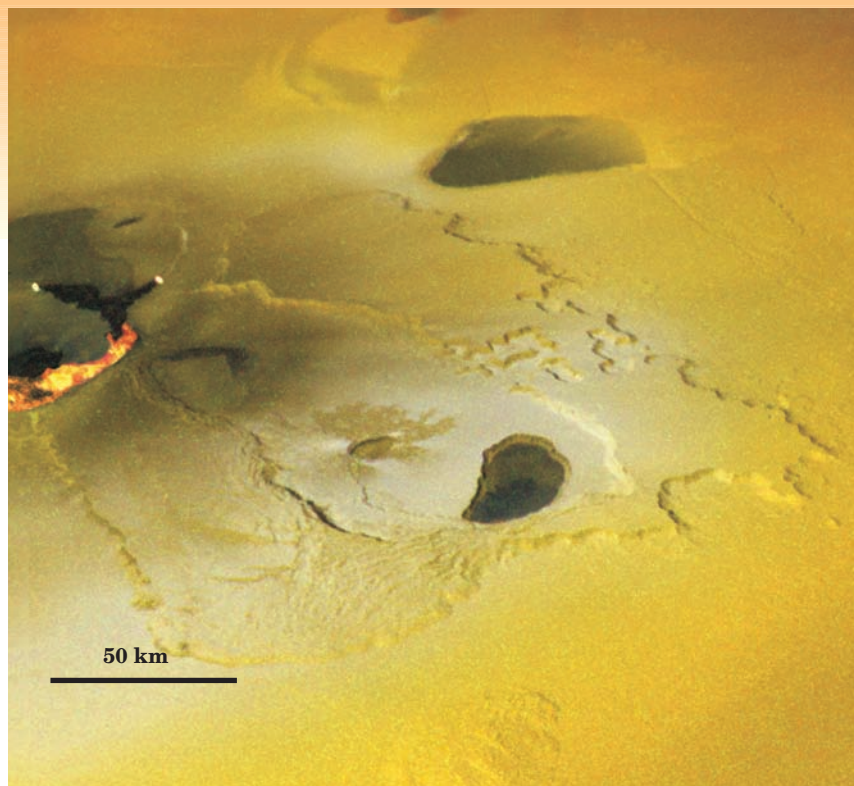
taken by *Galileo* while the moon was being eclipsed by Jupiter show patchy auroral glows from volcanic SO_2 and a faint limb glow from a thin global atomic-oxygen atmosphere.³ Ionospheric electron densities derived from radio occultation data show a strong asymmetry related to the effects of a rapidly rotating plasma overtaking the moon and compressing its atmosphere and ionosphere. *Galileo* detected ionospheres at each of the other moons as well. All exhibit plasma-related asymmetries similar to those seen at Io.

The icy satellites lack strong volcanic sources, so the origin of their atmospheric gases appears to be sublimation and sputtering of surface ices. On Europa and Ganymede, the primary source is probably water ice. Observations from *HST* have identified molecular oxygen on both of those satellites⁴ and UV observations of Ganymede made by *Galileo* show an extended hydrogen exosphere, a finding consistent with a water source.⁵ Oxygen has not yet been detected on Callisto, but near-IR spectra demonstrated a tenuous carbon dioxide atmosphere around it.⁶

Materials other than ice

Water ice and frost are ubiquitous on the surfaces of all the Galilean satellites except volcanic Io. Darker, non-ice constituents are mixed with the ice in varying degrees and create the brightness and color variations seen on each satellite. Scientists believe the darker material is similar to the dust and rock that originally accumulated in or condensed along with the ice from Jupiter's circumplanetary nebula: It consists of rocky minerals—probably hydrated—and carbon-rich organic material similar to that found in primitive meteorites. Some of the material may have been delivered to the satellites by meteorites. *Galileo*'s near-IR spectral mapper has given new insights into the nature of the non-ice surface materials and has provided some surprises as well.⁷

Spectra of Callisto show the clearest signature of the non-ice material, which is present in larger quantities on that satellite's ancient cratered surface than on the surfaces of younger Ganymede and Europa. The spectral band in the 3- to 5- μm range—a region largely inaccessible to Earth-based spectroscopy due to strong CO_2 absorptions in Earth's atmosphere—reveals several new key absorption features. Indeed, the strongest of those features is due to CO_2 on Callisto's surface. Analysis of the absorption suggests that it is due to a condensed form of CO_2 , neither pure solid nor pure liquid, possibly in microdeposits or inclusions in the other surface material. Maps of CO_2 , such as that shown in figure 5, demonstrate that the compound is present in clearly defined local regions. A global pattern to the surface abundance is apparent as well: A greater quantity of CO_2 is evident in the hemisphere centered on 270° longitude, where magnetospheric plasma bombards the satellite. The correlation



with plasma bombardment suggests that the formation of CO_2 deposits is related to radiation-induced damage to surface materials or to radiation-induced chemical processes.

Spectrographers have identified two other absorption features in the 3- to 5- μm region as being due to SO_2 and the sulfur-hydrogen bond. Those surface constituents are also probably related to plasma and magnetospheric effects. Callisto's and the other icy satellites' low blue and UV reflectances also indicate sulfur; they have been attributed to sulfur ions implanted in the surface ices.

Callisto spectra also reveal two absorption features attributed to carbon-bearing compounds, one due to C-H bonds in hydrocarbons and one identified with C≡N bonds in complex compounds known as polycyclic aromatic hydrocarbons. Interestingly, both features, along with CO_2 absorption, are seen in spectra of interstellar dust and ice, which suggests that the carbon compounds on the surface of the icy moons are common in the material from which the planets and satellites formed.

All of the features identified on Callisto spectra show up in Ganymede spectra, but with somewhat lower signal-to-noise ratios. On Europa, water-ice absorption tends to dominate in the 3- to 5- μm spectral region, but one can still identify the CO_2 feature. The highly asymmetric characteristics of the water-ice absorptions in certain areas have motivated some scientists to suggest that Europa's surface contains hydrated material in addition to pure water ice: Likely candidates are hydrated magnesium- and sodium-bearing sulfate salts or cold sulfuric acid hydrate formed via radiation processing of surface materials. An argument for the salts is that Europa, like Io, appears to supply its own share of sodium and potassium to the Jovian magnetosphere. But salt and acid hydrate could well be present on the surface in varying amounts. The signature of the salty component of the surface is strongest in young disrupted areas on Europa. Salts may thus be the result of recent exchange between the surface and a putative subsurface ocean.

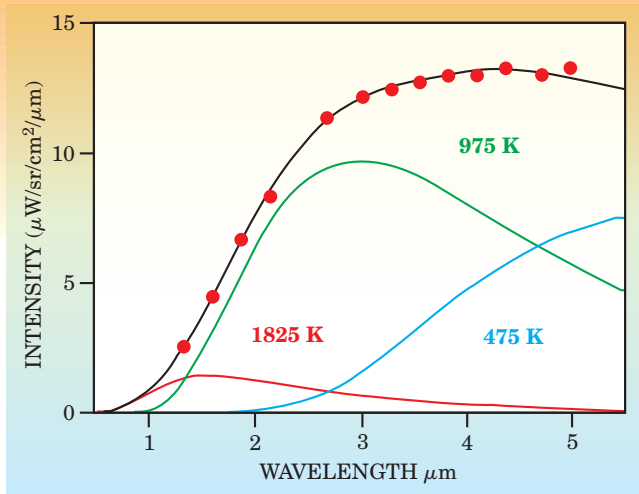


Figure 4. Temperatures of volcanic fluids are occasionally much higher than those observed in terrestrial volcanoes. The data shown here (red points) were taken by the near-infrared mapping spectrometer at the Pele/Pillan region of Io. The best fit curve (black) was derived from a three-temperature model (colored curves). Volcanic fluids from present-day Earth volcanoes do not reach temperatures as high as 1825 K. (Courtesy of NASA/Jet Propulsion Laboratory.)

Oceans

One of the most exciting results from the *Galileo* mission has been the evidence it gathered for global liquid-water oceans beneath the icy crusts of Europa, Ganymede, and Callisto. The planetary science community had considered such oceans a theoretical possibility ever since they were first proposed in the early 1970s. Since then, they have gone in and out of favor as scientists considered the latest theoretical models of the satellites' thermal histories and of water-ice properties. At issue is the competition between global heat sources, primarily radionuclide decay and tidal heating, and the ability of the satellites to lose heat through conduction and convection. If large-scale convection of ice dominates, then over geologic time scales, oceans tend to freeze. If the heat sources dominate, or if convection is not so efficient, then global oceans need not solidify. For the moment, *Galileo*'s data have tilted the

balance firmly to the pro-ocean direction.

Based on geologic evidence, Europa has always seemed the best candidate for an ocean. *Voyager* found that its surface was quite young; it lacked more than a handful of the large impact craters present in abundance on neighboring Ganymede and Callisto. In addition, the surface was covered with large-scale fracture patterns. Europa's surface features suggested recent overturn or resurfacing of the crust on a global scale, consistent with, although not clear proof of, a subsurface liquid layer. Europa is also geophysically favored to have an ocean, with potential tidal heating being considerably more intense than for Ganymede (though less so than for Io). *Galileo*'s imaging system confirmed the youthfulness of Europa's surface and provided spectacular high-resolution views of disrupted regions with fractured ice rafts tens of kilometers across, reminiscent of arctic sea ice (see figure 6).⁸ *Galileo* also revealed many regions of dome and pit structures that have been interpreted as the result of upwelling of warm ice from below.⁹

The major post-*Galileo* debate among planetary geologists has not been over the existence of an ocean but has concerned the thickness of the overlying ice layer. Several lines of evidence have been used to furnish estimates ranging from less than a kilometer to greater than about 20 km.¹⁰ Moment-of-inertia constraints from gravity data indicate an overall thickness of 75–150 km of water in any form, so

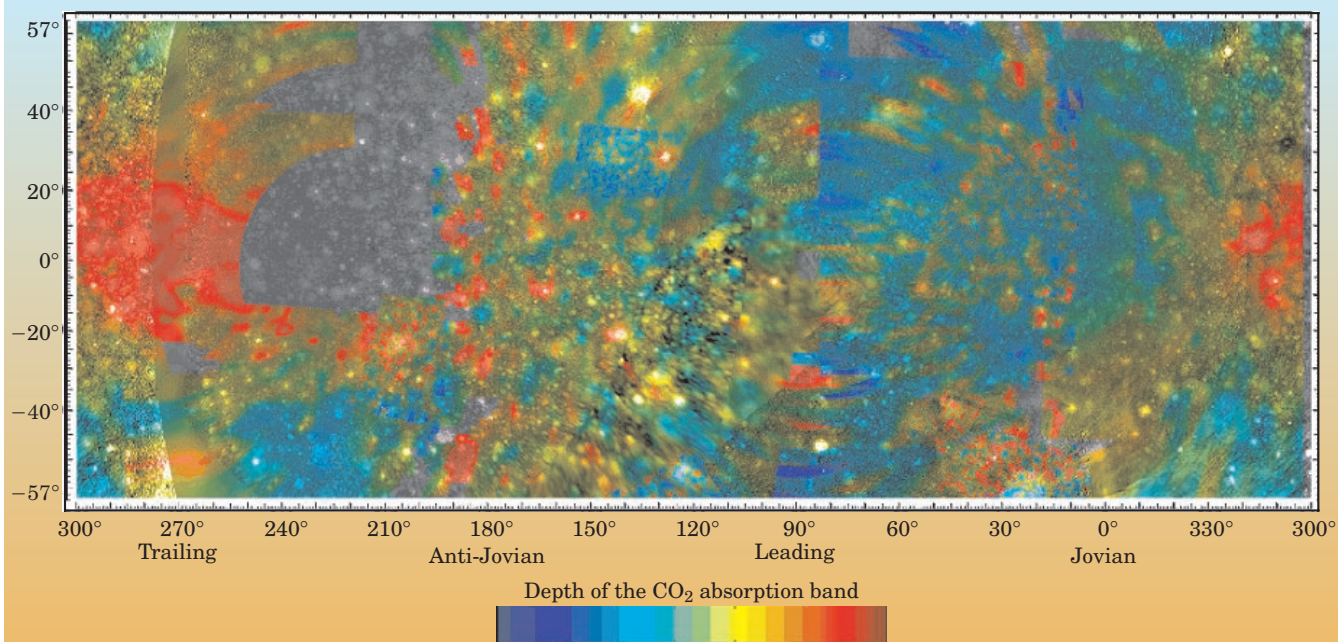


Figure 5. Carbon dioxide distribution on the surface of Callisto displays complicated local structures and a large region of concentration straddling the 270° longitude line. The large structure is around where the surface is bombarded by magnetospheric plasma. This spectrum was taken at 4.25 μm , in the near infrared. (Courtesy of NASA/Jet Propulsion Laboratory.)

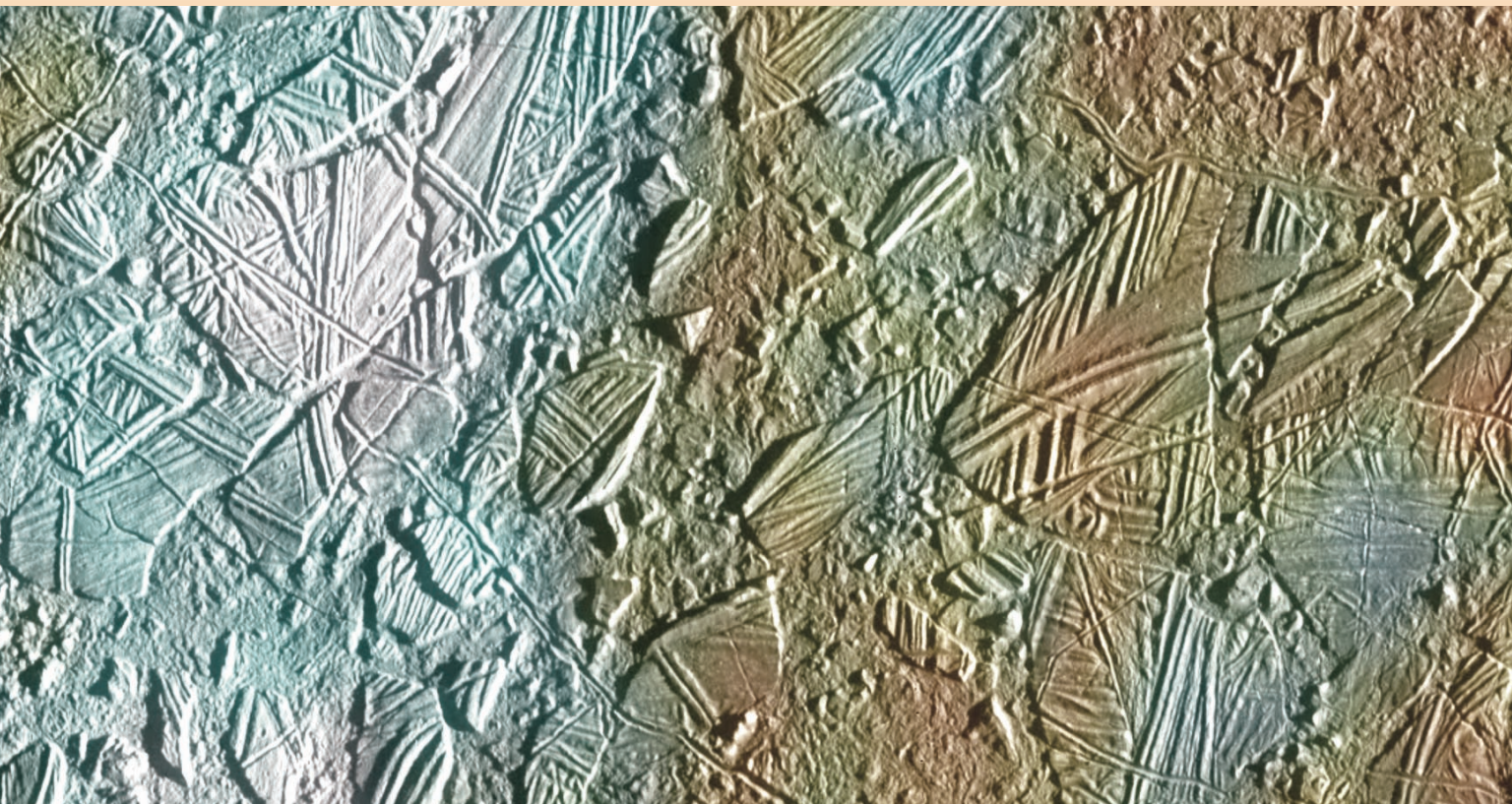


Figure 6. Europa's Conamara Chaos region presents an arctic landscape. This image shows an area 30 km × 70 km. The moon's smooth surface is one piece of evidence suggesting a subsurface ocean. (Courtesy of NASA/Jet Propulsion Laboratory.)

most working models of Europa's crustal structure yield ocean depths of roughly 50–100 km.

Evidence from magnetic perturbations

Images of the surfaces of Ganymede and Callisto show little direct evidence for subsurface liquid. Large, flat impact structures on Callisto and tectonic disruption of large portions of Ganymede's surface suggest that, at some time, the two moons had low-strength material such as warm ice in the upper few hundred kilometers of their surfaces. But the structural features do not point directly to currently existing liquid layers. Evidence for oceans on the two satellites, and the best evidence for a European ocean, comes from a seemingly unlikely source—magnetic field measurements.

After discovering Ganymede's dipolar internal magnetic field, investigators looked for evidence of similar intrinsic fields during close flybys of Europa and Callisto. During each encounter, *Galileo* observed significant perturbations in the background Jovian field. In any given encounter, the perturbations could be modeled as an effective dipole, but the dipole was different for each encounter. Thus, neither moon displayed a fixed, strong permanent field. The investigators found instead that the field perturbations almost exactly matched what one would expect from an electrically conducting sphere the size of the satellite when exposed to Jupiter's varying magnetic field. Ganymede also showed such a signal, superimposed on its intrinsic dipole.

Simple geometry explains the time-varying magnetic field seen by the Galilean satellites. The satellites orbit in Jupiter's equatorial plane, but the planet's field is tilted by about 10° from its spin axis. As a result, during

Jupiter's 10.5-hour rotation period, the satellites are exposed to a strong magnetic field that oscillates significantly in the direction to and from Jupiter but varies little in the north–south direction. An electrical conductor placed in such a time-varying field develops eddy currents that produce a magnetic field counter to the imposed field.

The inductive magnetic-field responses had not been anticipated because most planetary materials are poor electrical conductors. Rock and ice—even salt-rich ice—are not nearly conductive enough, and the satellites' ionospheres are not dense enough, to produce a sufficiently high effective conductivity. Investigators realized, however, that salty ocean water does have conductivity in the correct range. Interesting as that result is, it does not give precise information about the characteristics of the liquid layer. The only major requirement to produce the observed inductive effects is that a satellite's conducting layer be relatively close to its surface: The dipole magnetic field perturbations fall off with distance as $1/r^3$, so effects due to a deep conducting layer would fall off too rapidly to account for the *Galileo* observations. Given that the conducting layer is close to the surface, the inductive response only determines the product of the conductivity and thickness of the layer. For reasonable salt compositions and conductivities, the oceans must be at least a few kilometers thick, but they could be much thicker.¹¹

The structure of Europa's putative ocean is relatively simple. Water overlies a rocky seafloor and is capped by a crust of low-pressure ice. The crustal ice is in the same phase—called ice I—that we use to cool our drinks. It has a lower density than water and floats on Europa, just as it does on Earth. Ganymede's and Callisto's oceans are

more complex. To get at their characteristics, one must consider theoretical models and the phase diagram of ice. At high enough pressures, several solid forms of ice are denser than the liquid. Such pressures are reached inside Ganymede and Callisto at about 150–200 km below the surface. Thermal models that yield a stable ocean for those satellites thus have a fairly thick ice I upper crust (probably mixed with some rock for Callisto), consistent with the lack of photogeologic evidence of ocean interchange; a liquid layer; and a mantle of high-density ice (for Ganymede) or a rock and ice mixture (for Callisto)—a global ocean sandwich trapped between two icy layers.

Life?

The probable existence of liquid-water oceans, the presence of carbon-rich material, and the availability of energy in the form of radiogenic and tidal heat, sunlight, and particulate radiation have all combined to greatly increase the biological and astrobiological interest in the icy Galilean satellites. Although they orbit far outside the usual definition of the habitable zone in our solar system, the three moons may be capable of sustaining life, at least at the microbial level, and may also be places where life could arise. Europa has so far drawn the most attention, because its ocean environment might have many attributes in common with Earth's deep hydrothermal vent systems—in particular, a rocky sea floor and possibly volcanic activity. Only further exploration can determine whether the environmental conditions of the icy satellites have actually led to past or present life on those worlds.

Galileo's exciting discoveries have resulted in ambitious plans by the science community for future exploration of the satellites. The National Research Council's recently completed survey of Solar System exploration recommended a *Europa Geophysical Explorer* as its priority flagship mission and identified high-priority investigations of Io, Ganymede, and Europa for future missions. NASA is now developing a *Jupiter Icy Moons Orbiter* to respond to those priorities. *JIMO* would be the first spacecraft to use nuclear electric propulsion. It would also be capable of orbiting each of the icy Galilean moons while carrying a massive payload able to support advanced high-power instrumentation and data transfer rates 100 times greater than is possible in current missions. The science goals and objectives for *JIMO* derive directly from the rich legacy of discovery handed down by *Galileo's* now completed mission.

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