Galileo Explores the Galilean Moons

Tidal tugs sculpt Jovian satellites

By RON COWEN

By January of 1610, Galileo Galilei had fashioned a telescope capable of magnifying heavenly objects 1,000 times. On January 10, he climbed to the top floor of his house in Florence and took his customary window seat, pointing his telescope skyward over the domes of the ornate San Antonio Basilica.

Homing in on the planet Jupiter, Galileo made a momentous discovery: Three fuzzy white orbs, brighter than the stars around them, hovered near the planet. Within days, he had spied a fourth.

Today, these four large satellites of Jupiter—the Galilean moons Io, Europa, Ganymede, and Callisto—are becoming familiar faces in the firmament. Hints of their distinctive personalities came from the two Voyager spacecraft, which in 1979 sped past the Jovian system at a great distance. Now these moons, the largest of Jupiter's 14 known satellites, are being brought into sharper focus by high-resolution images, magnetic measurements, and spectra collected by another Galileo—the NASA craft that has nearly completed its main mission, a 2-year tour of the Jovian system.

A study in extremes, the moons range from searingly hot Io, which spews more lava per unit area than any other object in the solar system, to frigid Callisto, an icy mudball nearly as big as Mercury that appears to have been geologically dead for billions of years. In between lie mysterious Europa, whose cracked carapace hints that an ocean—and perhaps the rudiments of life—lurk beneath, and wrinkled Ganymede, whose tortured surface, a jumble of fractures, cracks, and faults, attests to a violent past.

Yet these disparate worlds have a common thread, says Galileo mission scientist Torrence V. Johnson of NASA's Jet Propulsion Laboratory in Pasadena, Calif. The three innermost moons are caught in a gravitational tug-of-war with Jupiter and with each other. When any one moon shifts position, the other two readjust, keeping the satellite locked in battle. Scientists estimate that Callisto won't join the fray for another 10 billion years.

The tug-of-war distorts these participating bodies, generating on their solid surfaces the equivalent of an ocean tide. Because Io, Europa, and Ganymede have slightly elliptical paths around Jupiter, the tides vary in strength during each orbit, causing the moons' surfaces to flex. The flexing generates heat, pumping energy into the moons and profoundly affecting their character and evolution.

"What we've been seeing in the Jovian system, with the exception of Callisto, is the importance of tides," says theorist David J. Stevenson of the California Institute of Technology in Pasadena. "That is not a new story, but it has been reemphasized by the results of the Galileo mission."

"Geology is basically driven by the heat the planet [or moon] has available to it and how it gets rid of it," notes Johnson. Coursing through solid bodies in the solar system, heat can fuel volcanic eruptions, fracture a smooth surface, or unleash a torrential flood.

Before Voyager, planetary scientists focused on two sources of heat, both associated with the earliest history of a planetary body. As chunks of rock and ice slammed into each other to build a moon or planet, kinetic energy changed into heat. Subsequently, the decay of radioisotopes provided additional pulses of energy.

In this simple model, larger bodies cool more slowly and are more likely to remain active than smaller ones. Certainly, this holds true for the terrestrial planets: Earth and Venus still undergo volcanic upheavals, while tiny Mercury and Earth's moon are thought to have been quiescent for 3.5 billion years. Mars, midway in size between Venus and Mercury, is believed to have had volcanic activity sometime in the past couple of billion years.

So far so good. But in 1979, the model failed spectacularly. The Voyager craft revealed that Io, about the size of Earth's moon, was the most volcanically active body in the solar system. "It was resurfacing even as we watched," notes Johnson.

Researchers had neglected the role of tidal heating.

Indeed, Galileo's wealth of data—high-resolution images, magnetic field measurements, and gravity maps—all suggest that Io, Europa, and Ganymede have undergone periods of tidal heating strong enough to produce internal melting and major upheavals on the surface. Some of the volcanic hot spots on Io have temperatures exceeding 1,400 kelvins; moreover, the heat pouring out of this moon is enough to have melted it some 4,000 times, reported Alfred S. McEwen of the University of Arizona in Tucson last month at a meeting of the American Astronomical Society in Cambridge, Mass.

Tidal heating may also drive magnetic activity. Researchers have been unable to determine whether the field detected by Galileo near Io is induced by Jupiter or intrinsic to the moon, says Margaret G. Kivelson of the University of California, Los Angeles. If Io generates its own field, the moon almost certainly consists of a molten iron or iron-sulfide core surrounded by rock, says Kivelson, who oversees Galileo's magnetometer experiment. She and her colleagues suspect that Io may generate a magnetic field by the same mechanism that operates within Earth: Fluid set in motion by heat from an iron-rich core creates electric currents that, in turn, produce a field.

Magnetic measurements performed near Europa late last year are even less conclusive, Kivelson and her colleagues noted in the May 23 SCIENCE. Come December, however, when Galileo begins a concentrated 2-year study of this moon, the craft will pass within 300 kilometers of the surface. Galileo's magnetometer should have a good chance of ferreting out a magnetic field if Europa possesses one, says Kivelson. A Europan magnetic field, if it has an origin similar to Earth's, would suggest that Europa, too, has an inner core that heats and continuously overturns a surrounding layer of liquid.

Tidal heat may also serve to keep water beneath Europa's surface from turning to ice, says Kivelson.

The presence of a magnetic cocoon around Europa would thrill biologists. Just as Earth's magnetic field shields living things from exposure to harmful, energetic charged particles from the sun, so a magnetic field on Europa would repel some of the particles generated by Jupiter's intense magnetosphere. In combination with a supply of water and heat—two of the necessities for sustaining life on Earth—a magnetic field would seem to increase the likelihood that Europa nurtures life, Johnson says.

Measured changes in the speed of the spacecraft as it orbited the moon in late December and again in late February indicate that Europa's core is about as dense as that of Earth. Europa's interior consists either of a mixture of rock and metal or a metallic core surrounded by a rocky mantle, the latter being more consistent with an intrinsic magnetic field, reported John D. Anderson of JPL and his collaborators in the May 23 SCIENCE. The rock and metal are enclosed in a shell, 100 to 200 km thick, of liquid or frozen water.

For now, Galileo's images provide some of the most compelling evidence that Europa possessed an outer layer of water, or at least slushy ice, in the recent past. Earlier in the mission, the craft spied large wedges of ice that looked like pieces of a jigsaw puzzle that had been pulled apart and rotated. Reminiscent of sea ice, the wedges indicate that there might be a layer of water or soft ice a few tens of kilometers beneath the surface. "The crust has actually opened up, and new dark material has moved in between [the wedges]," says Robert T. Pappalardo of Brown University in Providence , R.I.

In other regions, Galileo homed in on dark bands, first spied by Voyager, that cut across Europa's icy plains. The younger bands lie at an angle to the older ones, an analysis of Galileo images has revealed. This suggests that the stresses that produced these bands have shifted.

At last month's astronomy meeting, Richard Greenberg of the University of Arizona and his collaborators proposed that two related forces may have sculpted these and other features. Tidal deformations on Europa, which alternately contract and expand the surface each day (the equivalent of 3.5 Earth days), are tiny but could produce some of the bands over a period of about 10,000 years.

A second driving mechanism stems from Europa's rotation. If the moon's surface spins faster than its interior—an indication that a layer of liquid water separates the icy surface from the denser core—cracks and ridges would appear in new orientations.

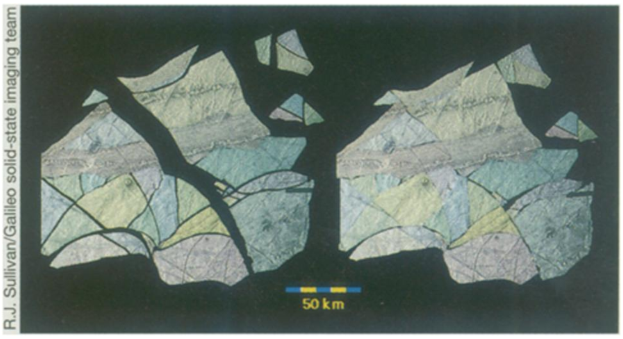
Once a crack appears on the surface, the daily tide on Europa would open and close it, notes Greenberg. When a crack is open, water seeps up from below, filling the crack and partially freezing, he suggests. When the tide closes the crack, the newly frozen material is squeezed out onto the surface, forming ridges similar to those observed by Galileo, he adds.

Last May, at a meeting of the American Geophysical Union in Baltimore, Pappalardo reported that Europa's surface shows evidence of cracks on much finer scales. The size of the cracks implies that they lie within a brittle ice layer only 200 meters thick and float above a layer of warmer ice with liquid water beneath. Intriguingly, this cracked facade has few craters, an indication of recent, major changes on the surface of Europa, which would have obliterated these pockmarks.

"What are the chances that this body remained active and liquid inside up to a few hundred million years ago and then froze on us just like that?" asks Johnson. "That requires a lot of fine-tuning from nature. Instead, it looks like nature is pumping a lot of energy into all of these moons, and they're responding."

Ganymede presents a particular puzzle. The strength of its magnetic field, along with gravity data, suggests that Ganymede has a metallic core the size of Io's, surrounded by an 800-km shell of rock and an outer shell of ice, also 800 km thick. The moon's surface, moreover, is raked with furrows and ridges but lacks craters, suggesting it formed recently.

"It's tempting to say that tidal heating came along and brought stuff to the surface from the inside or softened and deformed the surface so much that previous craters were obliterated," notes Stevenson. However, he adds, the amount of tidal heating available to Ganymede today isn't nearly enough to produce the moon's scars, its three-layer composition, or its magnetic field.



R.J. Sullivan/Galileo solid-state imaging team

Left: Wedge-shaped pieces of Europa's surface are separated by dark gaps. Right: In this simulation, the wedges, some of which had to be rotated, now fit together like pieces of a jigsaw puzzle. The good fit suggests that the plates separated when water or slushy ice seeped gently up through cracks and froze.

Six years ago, as a way to explain the striking differences between Ganymede and its same-size sister, Callisto, Renu Malhotra of the Lunar and Planetary Institute in Houston proposed that in the past, Ganymede had experienced stronger tidal heating. In an upcoming article in ICARUS, she, Stevenson, and Adam P. Showman of Caltech detail their argument.

When Jupiter first formed, Malhotra and her colleagues contend, none of the moons had the special relationships they now have to each other. Over a period that may have lasted a few hundred million years, Jupiter transferred some of its rotational energy to its nearest moon, Io, in the same way that Earth has gradually slowed, giving up some of its spin to its moon. In response, Io began spiraling outward—until it encountered the gravity of its nearest sibling, Europa.

The tug exerted on Io by Europa was then, and still is, minuscule, notes Johnson. It wields less than one ten-thousandth the pull of Jupiter. However, the orbits of the two moons obey a special rule. For every revolution Europa makes around Jupiter, Io makes two.

"For however long this interaction has been going on, these two moons have been locked together," says Johnson. "Europa is overhead giving Io a kick in just the same place" every 2 days. The cumulative effect is to move Io into a more elliptical orbit, where it experiences larger fluctuations in Jupiter's pull. As a result, tidal heating is enhanced. Europa, to a lesser degree, follows suit and also moves into a more elliptical orbit.

Locked together and still gaining energy from Jupiter, Io and Europa began spiraling out as a pair. After another billion years or so, the two moons were in the right place at the right time to take on a third partner, Ganymede, which had been orbiting Jupiter solo. The new collaboration elongated Ganymede's orbit and increased the moon's tidal heating. "In order to generate [Ganymede's] magnetic field, you not only need to dump all that heat into Ganymede, you also need to preserve it for a long time," says Malhotra.

Eventually, this pas de trois became looser. Today, Ganymede goes around Jupiter about once for every two passes of Europa, but the alignment is not nearly as rigid as that between Io and Europa.

"The important point is that the system has not caught up with Callisto yet," says Stevenson. "The three other moons are out in this choreographed resonance, this dance. But Callisto has not joined the party yet."

Scientists don't know when Callisto may join, "because we would need to know where these satellites were at time zero, and nobody took a snapshot 4.5 billion years ago," Stevenson adds.

Several planetary scientists say that even without tidal heating, it's a mystery why Callisto appears to be a uniform blob of rock and ice with no magnetic field. James W. Head of Brown University notes that even the small amount of heat left over from Callisto's formation might have been expected to partially melt the moon, causing its denser material to sink to the core.

"I'm dumbfounded," says Head.

During the craft's extended mission, for which four additional flybys of Callisto are planned, researchers will seek to determine if the moon is truly homogenous. With eight more visits to Europa and two close-up explorations of Io scheduled between the end of the year and 1999, Galileo's pale white orbs may soon yield more of their secrets. □