testinal microbial milieu, which may alter epithelial permeability, admitting an influx of gluten and other antigens.

The multiple levels of immune regulation explain the observed broad spectrum of gluten sensitivity in patients with celiac sprue, and will allow us to test several intervention strategies. With the ease of obtaining duodenal biopsies, immunomodulatory therapies can be verified in celiac sprue patients, an approach that should benefit all individuals who suffer from immune diseases of the intestinal system.

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PERSPECTIVES: PLANETARY SCIENCE

Active Volcanism on Io

Alfred S. McEwen

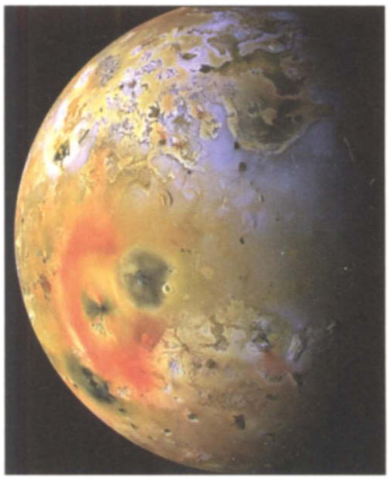
Jupiter's moon Io (see the first figure) is a bizarre world with hundreds of active volcanoes, high rugged mountains, a colorful surface rich in sulfurous materials, and giant (up to 500 km high) plumes of gas and dust that drive a thin atmosphere. High-resolution data returned by the Galileo spacecraft resolve some longstanding questions regarding Io's volcanism and pose new questions about its internal structure.

The four Galilean moons of Jupiter are planet-sized worlds. The three innermost moons have resonant orbits: Each time Ganymede orbits once, Europa orbits twice and Io four times, leading to substantial tidal heating of Europa and intense tidal heating of Io. In Greek mythology, Io was a nymph who was changed into a heifer by her lover Zeus but later regained her form. Likewise, the massive Jupiter (Zeus) periodically deforms Io, which has an eccentric orbit forced by the periodic tugs of Europa and Ganymede. The resulting world may provide clues to understanding very ancient volcanism on Earth.

The Voyager 1 flyby in 1979 first revealed the exotic surface and active volcanism of Io (*1*). The nature of the volcanism was hotly debated. Some scientists, such as Carl Sagan (*2*), argued that sulfur volcanism was burying a silicate subcrust. Others, such as Michael Carr (*3*), argued for silicate volcanism and crust (similar to that on Earth) with thin sulfurous coatings.

Sulfurous volcanism could not produce temperatures above ~700 K, whereas basaltic lavas on Earth range from 1300 to 1450 K. Voyager instruments and Voyager-era telescopic observations revealed hot spots with temperatures of up to 650 K, consistent with sulfur volcanism. But these measurements lacked the sensitivity and wavelength coverage needed to detect small areas with higher temperatures.

The first convincing evidence for surfaces too hot for sulfur volcanism was acquired in 1986 (*4*). During the next 10 years, ground-based measurements yielded several other detections of such high temperatures, and it became apparent that there were at least a few sporadically active silicate eruptions. But a second key test—the spectral reflectance of the dark regions suspected of being silicate lavas—could not be accomplished from Earth-based telescopes. In recent years, NASA's Galileo mission has provided some of these missing data after overcoming some formidable obstacles.



Global view of Jupiter's moon Io. Enhanced color composite image from data obtained in September 1997 by Galileo. One of the most dramatic changes from previous images was the appearance of a new dark spot (upper right edge of the big red ring of Pele), 400 km in diameter, which surrounds the volcanic center Pillan Patera.

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When the Galileo spacecraft was launched in 1989 after delays such as the shuttle Challenger explosion, it had to take a longer, less direct path to Jupiter than originally planned. After launch, the umbrella-like high-gain antenna failed to open properly. The mission team was forced to drastically revise the science planning, returning just a small fraction of the expected data via a small, low-gain antenna.

Galileo included much more sensitive instruments than Voyager, such as the Solid State Imaging (SSI) system (sensitive from 400 to 1000 nm) and the Near-Infrared Mapping Spectrometer (NIMS) (sensitive from 700 to 5200 nm). SSI could detect only areas hotter than ~700 K and usually when Io was in eclipse (in Jupiter's shadow) to eliminate reflected and scattered light. NIMS had the ideal spectral coverage for detecting both the temperatures and spectral reflectances expected from silicate lavas, but had limited spatial resolution (120 km or more), except during the one close Io flyby in December 1995 expected when Galileo first arrived at Jupiter.

Unfortunately, Galileo's troubles were not over. Because of a tape recorder anomaly, no remote-sensing data of Io's surface were collected during the Io flyby. Galileo subsequently proceeded to be a great success, with several extensions beyond the 2-year nominal mission, including six close Io flybys. But by the time of the first return to Io in 1999, the spectral grating of NIMS had become stuck and several detectors were dead or degraded. NIMS could therefore acquire useful data at only 13 rather than hundreds of wavelengths. The greatest scientific toll of the early tape recorder anomaly was the loss of NIMS spectra that could spatially resolve the dark patches to determine their compositions.

Despite these early troubles, the Galileo mission has provided unprecedented insights into Io's volcanism. The first distant Galileo observations of Io were made in the summer of 1996. The first SSI image of Io in eclipse revealed eight definite hot spots and several other likely sites of active silicate eruptions. The first NIMS images revealed 14 hot spots with single-temperature fits ranging from ~400 to 600 K; more sophisticated models revealed hot spots with temperatures above ~1000 K in most or all of these images. By 1998, Galileo had identified a total of 41 hot spots (*5*), all in the dark patches that cover only about 1.4% of Io's otherwise bright sur-

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face (6). Galileo also recorded color and albedo changes on the surface, an association between bright red deposits and silicate vents, auroral glows, plume observations, and maps of SO_2 distributions.

Between late 1999 and early 2002, Galileo completed a total of six close Io flybys. No further flybys are possible before Galileo plunges into Jupiter in 2003. Io's orbit lies deep within Jupiter's energetic radiation belts, which is why Galileo did not go close to it until near the end of its mission. The radiation caused several problems, such as scrambled images and spacecraft anomalies that precluded observations. Nevertheless, many useful high-resolution observations were acquired by SSI, NIMS, and the Photopolarimeter Radiometer (PPR).

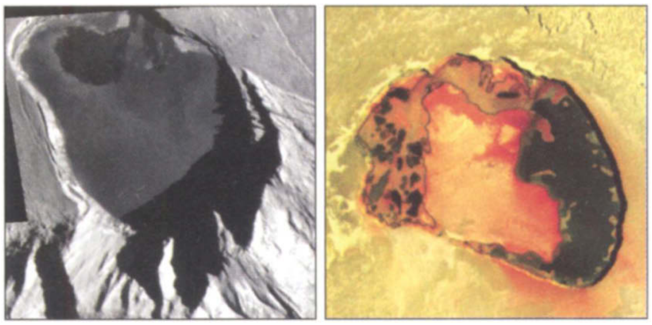
The closer the spacecraft got to Io, the greater the density of hot spots observed by NIMS. Lopes *et al.* (7) estimated a total of 150 to 300 major hot spots on Io. SSI and NIMS revealed many details about vent regions, lava flows, lava fountains, lava lakes, mountains, paterae (caldera-like depressions), plumes, mass-wasting, and SO_2 frost (8). PPR provided background temperature maps to constrain global heat flow, and detected temperature patterns suggesting that Loki is a giant lava lake (9).

The last Io observations in 2000–2001 yielded two surprising results (during the very last Io flyby in 2002, almost all data were lost). After no detections of polar plumes during the first 4 years of Galileo monitoring, there was evidence for four giant (up to 500 km high) plumes near the north pole. The data further suggested that lava lakes are abundant on Io (see the second figure) and may be a significant mechanism for heat loss.

Perhaps the most dramatic new volcanic eruption observed by Galileo was the 1997 eruption of Pillan Patera, which produced a new plume, a large dark deposit (see the first figure), and an intense hot spot. Temperature estimates of ~1800 K were well above that possible for basaltic volcanism (10). A dozen other hot spots also seemed to have such high temperatures, but the error bars were large and basaltic temperatures could not be excluded. The Pillan thermal signal was strong enough for us to be sure that very hot (>1500 K) surface areas were present. Furthermore, given the extremely rapid radiative cooling at high temperatures, the lava itself must be significantly (>100 K) hotter.

The hottest terrestrial lavas were erupted at 1700 to 1900 K. The great majority of these lavas are very ancient (age >2000 million years). These lavas provide some of the best evidence for a hotter mantle in the ancient Earth. But such eruptions have never been observed, the lavas are poorly preserved, and it remains unclear how they formed. The study of Io may thus provide important clues to understanding the early Earth.

The ancient high-temperature lavas on Earth are rich in magnesium, and Galileo color data support this compositional inference. SSI data revealed an absorption band at ~900 nm in the dark patches (6, 10). The best fit to these data came from laboratory spectra of orthopyroxenes, a silicate mineral rich in Mg that is abundant in some terrestrial rocks. All dark patches that were observed in infrared color had this spectral signature.



Lava lakes in Io? Two images acquired during Galileo's last successful Io encounter in October 2001 show volcanic depressions (paterae) that may contain lakes of molten lava covered by thin solid crusts. The patera on the left (in Tohil Mons) has a diameter of ~25 km, and colorful Tupan Patera (right) has a diameter of ~50 km.

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Furthermore, there were additional ground-based and Galileo measurements of very high temperatures. The data suggested that Mg-rich lava may be common on Io. The highest temperatures could only be detected during major new eruptive events, before the lava could spread out and the infrared spectra became dominated by cooling flows covering much larger areas than the smaller exposures of molten or recently molten lava. But if most of the lavas are Mg-rich, then the crust of Io must be ultramafic (especially rich in Fe and Mg). Indeed, it would be difficult to explain how dense, Mg-rich lavas could rise through a lower-density crust containing less Mg.

The idea that Io is an ultramafic world seems at odds with the well-understood process of magmatic differentiation. If Io has a solid lower mantle capped by a partially molten layer, as believed by most planetary geophysicists, then Io's crust should be strongly depleted in elements like Mg. As mantle rocks begin to melt, the first component to melt has a lower density. It segregates and rises toward the surface after ~10% melting of a given volume of the solid mantle. If Io's typical heat flow over geologic time is just 10% of today's value, then we can expect 10^{12} km^3 of silicate melt over the last 4000 million years—40 times the volume of Io. There should thus have been sufficient heat to melt 10% of Io's volume 400 times. After just four episodes of such partial melting, Io should have formed a low-density crust ~50 km thick (11). High-temperature, dense mafic or ultramafic lavas could only rise through the thick low-density crust under extraordinary circumstances.

One solution to this dilemma has been proposed by Keszthelyi *et al.* (12), who proposed that Io's mantle could be a crystal-rich magma ocean. Widespread ultramafic volcanism would be a natural consequence of this model, because the upper mantle would consist of orthopyroxene-rich magma with about the same density as the overlying crust. As lavas are deposited, the crustal layers sink and are eventually mixed back into the magma ocean, so a low-density crust cannot form.

This model predicts a hot mantle that would suppress convection in Io's large metal core, leading to a prediction that there should not be an intrinsic magnetic field around Io. This was confirmed by magnetometer measurements during Galileo's passes over the poles of Io in late 2001 (13). Although a magma ocean in Io would be stable, it is difficult to explain how Io first got into that state. Neither the magma ocean nor a partially molten mantle with rapid solid-state convection can be ruled out from currently available geophysical data, but only the magma ocean seems able to explain widespread ultramafic volcanism.

Is Io really an ultramafic world, or are we overinterpreting sparse data? Continued and improved telescopic observations will help, but a future spacecraft mission to Io seems essential to resolve this question. Although Io is too depleted in water to be a promising abode for life (as we know it), it is a remarkable natural laboratory to study physical and chemical processes, some of which provide insight into the early Earth.

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