Eos, Transactions, American Geophysical Union, Vol. 84, No. 33, 19 August 2003, Pages 313, 318

Extreme Volcanism on Io: Latest Insights at the End of Galileo Era

Galileo has now completed 7 years exploring Jupiter. The spacecraft obtained breathtaking views of the four major satellites, and studied Jupiter's clouds and atmospheric composition, rings, small satellites, and magnetic field. It had five successful close flybys and many distant observations of Io. Scientists already knew from Voyager and Earth-based astronomy that Io is by far the most volcanically active object in the solar system. Galileo has given us stunning color panoramas of Io's surface and unprecedented close views of erupting volcanoes (Figure 1) and the largest active flows observed anywhere. Among recent discoveries about Io, perhaps most astonishing since Voyager, is that some lavas possess emission temperatures greater than any lavas erupted on Earth today, and possibly since the start of Earth's geologic history. The Io science community has identified three alternative interpretations of Io's hottest lavas: (1) ultramafic material similar to komatiite; (2) superheated lava; or (3) an ultra-refractory substance deficient in silica and rich in Ca-Al oxides.

Untamed Hell

Io, with persistent hotspots and violent, short-lived outbursts, is far more volcanically active than the rest of the solar system combined. Over 100 active volcanic centers have been identified [*Lopes et al.*, 2001]. The magnitude of Io's volcanism is staggering compared to the 8–15 km^3/yr of lava erupted on Earth. Io releases > 3 x 10^{13} W/yr and > 500 km^3/yr of lava through volcanism. Having just 1.5% the mass of Earth, Io erupts over 30 times as much lava. Io could melt its entire mantle and crust 80 times since the origin of the solar system, or over 800 times for 10% partial melting [*Keszthelyi and McEwen*, 1997].

Lava temperatures currently provide the best clues for Io's lava compositions. Temperatures are calculated from measurements made by two Galileo instruments, the Solid-State Imager (SSI) and the Near Infrared Mapping Spectrometer (NIMS), and by ground-based telescopes, including high-resolution adaptive optic imaging from the Keck telescopes on Mauna Kea. SSI has eight filters covering 0.39 to 1.1 μm. NIMS has 408 channels from 0.7–5.2 μm, but late in the mission it was operable only in 13 channels across 1–4.7 μm [*Lopes-Gautier et al.*, 2000]. Temperatures determined by remote sensing data depend on the spatial resolution and wavelength range. Each pixel containing volcanic activity contains surfaces at a range of temperatures. All temperatures discussed below are minimum temperatures because of rapid cooling (Figure 2) and overestimated thermal emissivity.

One volcanic center on Io has well-constrained model temperatures higher than basalt: the 1997 Pillan eruption [*McEwen et al.*, 1998; *Davies et al.*, 2001]. This massive eruption produced lava flows >75 km long and a dark pyroclastic deposit > 400 km across [*Williams et al.*, 2001] (Figure 1a). A temperature of 1870 ±25 K was derived by fitting a model of thermal emissions from an advancing fountain-fed lava flow to the combined SSI-NIMS data set.

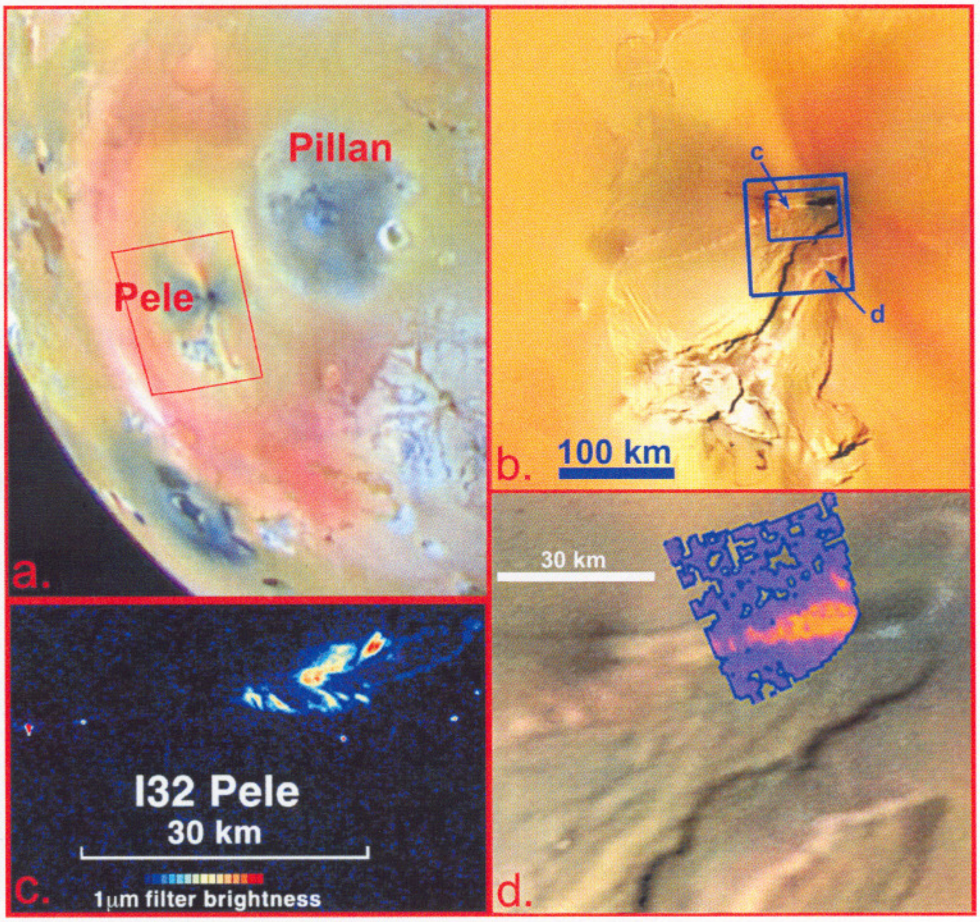

Fig. 1. (a) Color Galileo SSI scene of Pele and Pillan, 19 September 1997. The 1997 eruption of Pillan produced the Missouri-size dark ash deposit, which was absent when imaged on 4 April 1997. Pele's red ring, encompassing an area as large as Texas and Oklahoma combined, has been present since at least 1979. (b) Color Voyager image of Pele shows diffuse reddish and gray streaks radial to the area of highest thermal emission; slight changes were found later by Galileo. (c) Galileo SSI nighttime brightness image, 60 m/pixel, of glowing lava at Pele Patera (22 February 2000). Key features are (1) a central region of peak thermal output, possibly where the lava surface is rapidly overturning; (2) cooler regions probably having a stable crust; and (3) a ring of hotspots where a cooled lava crust may break up against the wall of a caldera. (d) NIMS data taken February 2000 over the Pele hotspot showing temperatures locally >1400 K (PIA02560).

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This temperature far exceeds basaltic lava temperatures (1400–1550 K) [*Davies et al.*,2001].

Further hints of high-temperature volcanism were found at Pele Patera (Figure 1). Pele, the site of an active lava lake [*McEwen et al.*,2000; *Davies et al*,.2001], was observed by Galileo NIMS and SSI and the Cassini ISS camera. The distant NIMS and SSI observations suggested that emissions from Pele were relatively invariant over several years and involved surfaces •1400 K [*Davies et al.*, 2001]. Cassini observations at Pele also showed a relatively constant thermal emission over a period of hours and color temperatures >1400 K (J. Radebaugh, University of Arizona, unpublished data, 2003). Constancy of thermal emission implies cooling and burial of lava as fast as new hot lava is erupted.

High-resolution (1–2 km/pixel) NIMS observations of Pele in darkness during February 2001 provide added constraints; *Lopes et al.* [2001] modeled emissions from 15 overlapping pixels where only the central parts of the spectra were saturated. The reported temperature for the hot component is 1760 ±210 K. An observation designed to constrain the highest temperatures at Pele was obtained on the last successful flyby of Io. High-spatial resolution (60 m/pixel), nighttime, two-filter, visible images (Figure 1c) showed vigorously active lava. Some scattered pixels provide very high color temperatures—in one location, 1600 ±220 K—but in general, temperatures >1450 K are difficult to distinguish from radiation noise (J. Radebaugh, University of Arizona, unpublished data, 2003). In sum, the temperatures at Pele admit either basaltic or ultramafic lava.

By far, the most energetic eruption seen on Io was not witnessed by Galileo. Data taken in February 2001 from the 10-m Keck II adaptive optics telescope showed a fast-spreading flow near Surt [*Marchis et al.*, 2002]. Two days after first seen, this flow outshined the most energetic eruption observed previously or since, but emissions at these wavelengths faded to undetectable levels in under a month. Calculated color temperatures require > 1470 K, allowing basaltic or ultramafic lava.

The SSI color and NIMS data from the reflectance spectrum of cool areas on Io suggest that most fresh lavas are primarily composed of orthopyroxene very rich in Mg, requiring ultramafic bulk compositions, according to analysis by Paul Geissler and others. Curiously lacking is the expected detection of olivine.

Io also possesses some unusual non-silicate eruptions. Sulfur lava may be indicated by low thermal emissions from some active, colored flows. Sulfur can be deposited by fumaroles, then melted and mobilized by hotter silicate flows and geothermal heat, as observed in Hawaii. Frozen sulfur dioxide and other sulfurous compounds are ubiquitous. The poisonous stuff is belched by volcanoes, spews from beneath advancing silicate flows, and condenses onto Io's vast plains. Sulfur dioxide probably fills a subsurface liquid "aquifer," which feeds spitting "warm springs" and erosive jets of SO_2, and drives the solar system's largest volcanic plumes.

A Model Underworld

Despite remaining uncertainties, a post-Galileo consensus finds high-temperature lavas on Io.

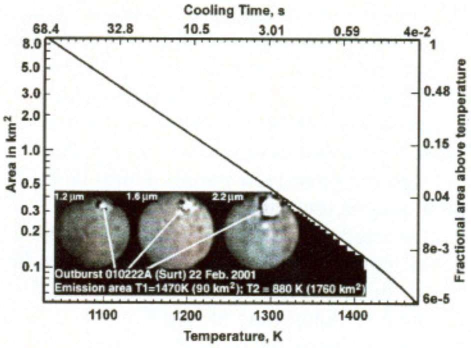

Fig. 2. The bright, massive Surt eruption (inset) observed by Marchis et al. *[2002] was modeled using the volcanic thermal emission model of* Davies et al. *[2001]. This Figure shows the area at a selected temperature and the time for each parcel of incandescent lava to cool to a given temperature. The total thermal emission is the sum of thermal emissions in each 1K bin, and the total hotspot area is the sum of areas in each 1K bin; for instance, there is 8.9 km² emitting at 1034 K, 8.8 km² at 1035 K, ...0.05 km² at 1475 K. The integrated thermal spectrum sums to what Marchis observed as one big, hot sub-pixel feature; areas hotter than 1034 K sum to 804 km². The area at 1000 K (10 km²) is more than an order of magnitude larger than seen at the peak of the 1997 Pillan eruption.*

Three hypotheses have been developed to account for the highest temperatures: the komatiite model, the superheating model, and "ceramic volcanism."

Komatiite. The komatiite model is a current baseline for much of the Io science community. The assumption is that Pillan's 1870 K minimum temperature closely approaches the actual hottest liquid lava temperature. This may be the case because these highest temperatures were derived from massive lava flows where turbulence may rapidly destroy chilled crust. Komatiites are ultramafic volcanic rocks with >18 weight % MgO, often containing olivine or clinopyroxene spinifex and cumulate textures. The likely presence in Io's lavas of large amounts of orthopyroxene is unusual for terrestrial komatiites. The only occurrence of orthopyroxene phenocryst-bearing komatiites on Earth is in the Commondale greenstone belt, South Africa. These rocks contain unique orthopyroxene spinifex crystals and were derived from a ~31% MgO, ~50% SiO_2 komatiite liquid, which had a liquidus temperature ~1884 K [*Williams et al.*, 2000], similar to that calculated for Io's 1997 Pillan eruption [*Davies et al.*, 2001]. If the lavas are as deficient in FeO as the SSI color data imply, it requires significant and interesting differences from any terrestrial lava, requiring greater reduction of iron to metal and presumably sequestration in Io's core. Deficient FeO could potentially relate to derivation from a precursor resembling an enstatite chondrite. Alternatively, other processes may remove FeO from Io's crust and mantle. Extreme Mg enrichment suggests very large degrees of partial melting of Io's mantle; a global magma ocean is possible.

Superheating. Magma can be superheated by rapid ascent from a deep, high-pressure source. Because melting temperatures of dry silicate rocks increase with pressure, the erupted lava can be significantly hotter than the lava's melting temperature at surface pressure. However, for lava at 1870 K to have a basaltic composition (with liquidus melting temperatures ~1400–1550 K at 1 bar), the magma would have to ascend rapidly from nearly 1,000 km deep with little cooling in transit. Though no record of such an eruption exists on Earth, magma may have erupted from nearly such depths on Earth's moon. Alternatively, Io's magmas could be heated near the surface by the electrical induction currents and plasma currents bathing Io. Heating in a tidally deforming dike is inadequate to heat basaltic lavas to the highest temperatures seen on Io, according to our calculations.

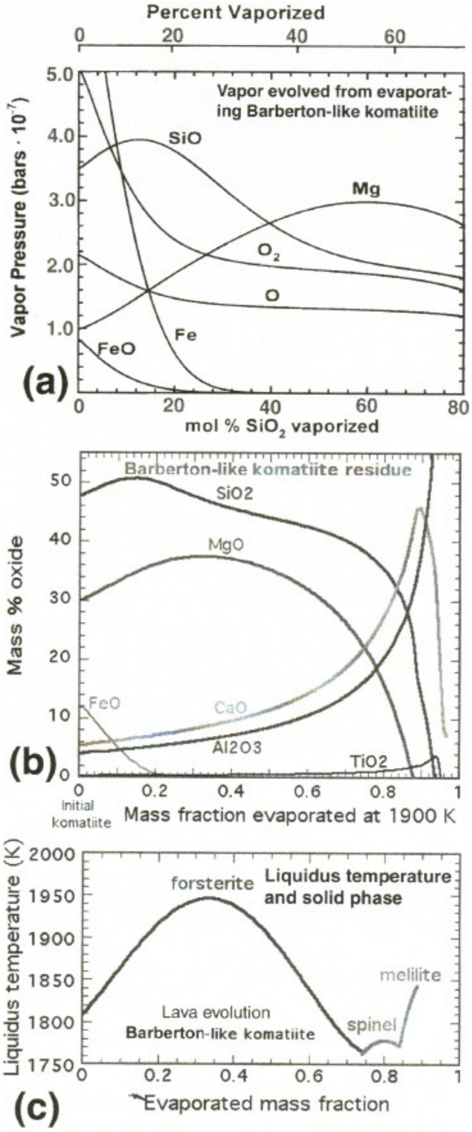

Fig. 3. Fractional vaporization model for an initial Barberton-like komatiite magma at 1900 K. (a) Evolution of the oxide and metal partial vapor pressures and composition. (b) Composition of residual refractory liquid as it evaporates. (c) Evolution of liquidus temperature and liquidus solid phase corresponding to the liquid compositions in panel (b).

Vapor distillation and "ceramic volcanism." Lava outside the basalt-peridotite-komatiite system is conceivable due to Io's unique history of intense, high-temperature magmatic processing. The partial vapor pressures of SiO, Mg, Fe, FeO, and other gases of common oxide and silicate systems exceed nanobars at 1500 K and approach microbars at 1900 K [*Stolyarova and Semenov*, 1994]. Vaporization of metals from hot lava can be significant when exposed on flow surfaces and through cracks in solidifying crusts, especially if fluxed by sulfurous volatiles. Vapor pressures and lava evolution due to fractional vaporization were calculated for the system Si-Na-K-Mg-Fe-Ca-Al-Ti-O (L. Schaefer and B. Fegley, Washington University, unpublished data, 2002). Results for an initial Barberton high-MgO komatiite at 1900 K are given in Figure 3. Initial vapors are dominated by Na and K (not shown) and oxygen species. Pressures of other gases, though lower, are orders of magnitude larger than Io's ambient surface pressure. Following rapid loss of alkalis, vapors are dominated by SiO, Fe, FeO, Mg, O_2, and O (Figure 3a). If metal and oxide vapors can be lost entirely from Io or cold-trapped at stable sites, compositional evolution of evaporated lava residues would affect igneous phase equilibria and the temperature of subsequent eruptions. Refractory lava residues lack the amounts of SiO_2 and FeO in common silicate lavas (Figure 3b) and may have extraordinary liquidus temperatures (Figure 3c).

Questions Still to be Answered

The epic tour of the Jovian system by Galileo has expanded our vision of what is possible in this universe. Io has its own unique and hyperactive behavior that has been produced by and may have affected its global chemical evolution. Unsolved puzzles regard the range of silicate lava compositions and eruption temperatures and the mechanisms by which such large volumes of lava are transported through the crust. How can Io maintain its high magma temperatures without being almost totally molten? Is Io a crusted magma ocean, and if so, how does Io maintain a sufficiently thick and strong lithosphere to support mountains higher than Mount Everest? Is Io a refractory cinder-like body, like a giant meteoritic calcium-aluminum-rich inclusion (with added volatiles)? Why does Io have an extremely volatile, sulfur-rich surface, yet water, carbon dioxide, and many other volatiles are absent? How are we to reconcile Io's peculiar volatility with high-temperature global processing?

Future space missions and astronomical observations could give definitive answers to these questions.

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