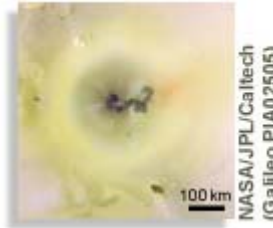


Hot Idea

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IO (Prometheus volcano)



Jupiter's Hot, Mushy Moon

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Jupiter's moon Io is the most volcanically active body in the Solar System. Observations by instruments on the [Galileo](#) spacecraft and on telescopes atop Mauna Kea in Hawai'i indicate that lava flows on Io are surprisingly hot, over 1200 °C and possibly as much as 1300 °C; a few areas might have lava flows as hot as 1500 °C. Such high temperatures imply that the lava flows are composed of rock that formed by a very large amount of melting of Io's mantle. This has led Laszlo Keszthelyi and Alfred S. McEwen of the University of Arizona and me to reawaken an old hypothesis that suggests that the interior of Io is a partially-molten mush of crystals and magma. The idea, which had fallen out of favor for a decade or two, explains high-temperature hot spots, mountains, calderas, and volcanic plains on Io. If correct, Io gives us an opportunity to study processes that operate in huge, global magma systems, which scientists believe were important during the early history of the Moon and Earth, and possibly other planetary bodies as well. Though far from proven, the idea that Io has a ocean of mushy magma beneath its crust can be tested with measurements by future spacecraft.

Reference:

Keszthelyi, L., McEwen, A. S., and Taylor, G. J. (1999) Revisiting the hypothesis of a mushy global magma ocean on Io. *Icarus*, v. 141, p. 415-419.

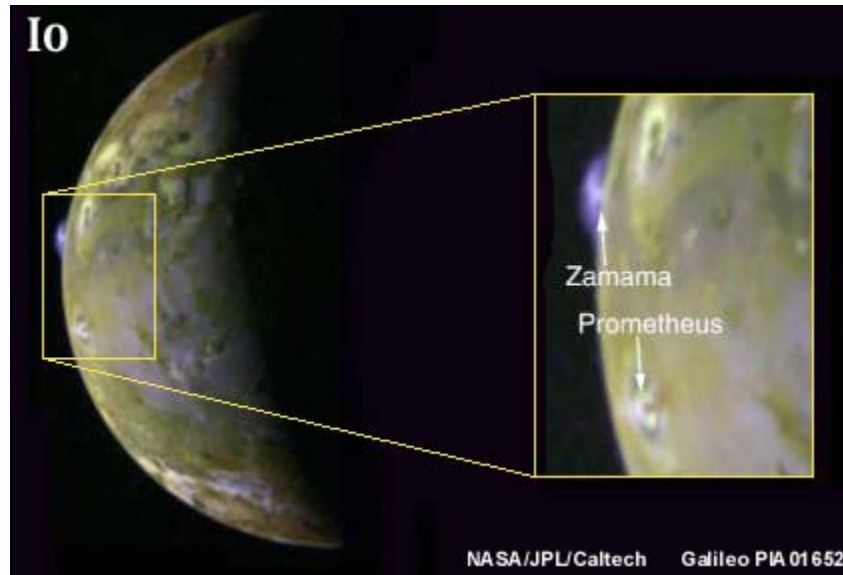
Hyperactive Volcanoes

In 1979, only a couple of months before the [Voyager](#) spacecraft zipped past Jupiter and its moons, Stan Peale, Pat Cassen, and R. T. Reynolds published a paper in *Science* predicting that Io was volcanically active. This bold prediction was made on the basis of an analysis of the way gravitational tugs from Jupiter and two other moons, Europa and Ganymede, affect Io. All the tugging causes the surface of Io to bulge up and down about 100 meters. Peale and coworkers argued that this flexing generates a huge amount of heat inside Io, possibly making the interior largely molten and probably causing widespread volcanism.

Peale, Cassen, and Reynolds must have been delighted when Voyager I photographed numerous active volcanoes on Io. Observations by Voyager II showed that some volcanoes were still active months later, and other volcanoes had started to erupt. In fact, Io is without a doubt the most volcanically active body in the Solar System. Its surface is constantly being covered with fresh lava. The resurfacing is so rapid that no impact craters are observed on its surface, a stark contrast to every other rocky body in the Solar System.

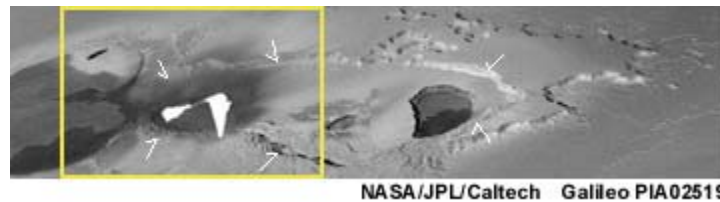
Spectacular images obtained by the Galileo spacecraft, which is in orbit around Jupiter, show that Io is still erupting promiscuously. The images **below** show active gaseous plumes from the volcanoes Zamama and Prometheus (image on the right is an enlargement of the boxed area). The plumes are about 100 km high.

Prometheus was also active during the 1979 Voyager flybys of Jupiter. The spatial resolution of the images is about 10 km per pixel.

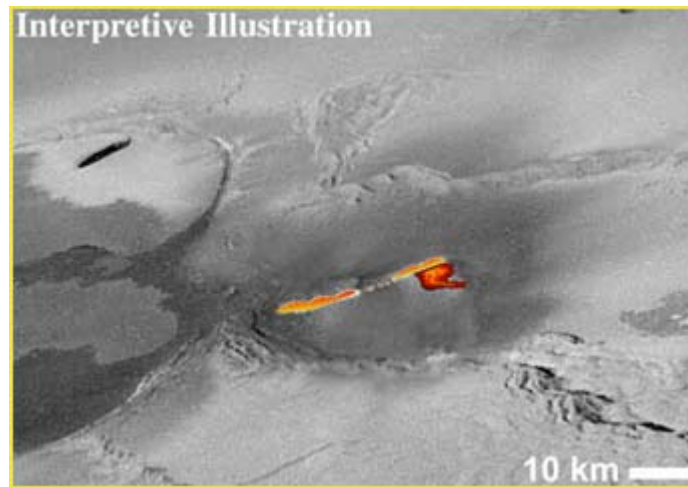


Airborne plumes of gas and dust from two of Io's active volcanoes, Zamama and Prometheus.

Lava also erupts vigorously on Io. The images **below** show lava shooting about 1.5 km high out of a long crack on Io's surface. The hot lava appears white in the **top** image because the lava was so hot that it overwhelmed the camera system and caused electrons to bleed into adjacent portions of the detector. The **bottom** image is a reconstruction of what the image would look like if no bleeding occurred. The hottest parts are colored red. The Galileo team estimates that the lava temperature during this eruption was as much as 1300 °C. The top image also shows a huge volcanic crater called a caldera, in which other calderas occur. The large caldera is 290 km by 100 km in size, much larger than any caldera on Earth. (For example, the caldera atop Kilauea Volcano in Hawai'i, Earth's most active volcano, is only 8km by 5 km.)



Hot lava (white areas on the left) and a caldera (margin indicated by small white arrows) on Io. Boxed area is shown below, enlarged.



What the scene would look like with red-hot lava flows.

Solid or Mushy?

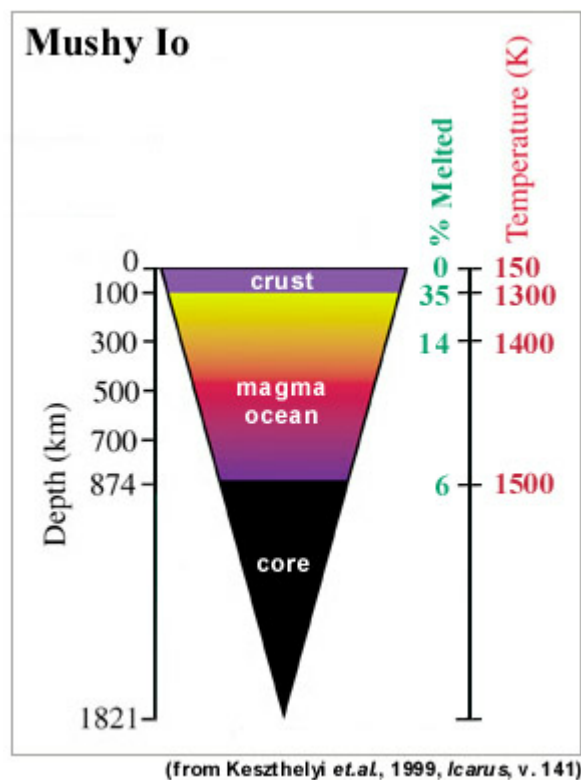
Peale, Cassen, and Reynolds were the first to suggest that Io might be largely molten inside. Their calculations had indicated that the gravitational yanks exerted on Io would dump so much energy inside it that it would remain molten. Thus, they depicted Io as having an ocean of magma beneath a thin, volcanic crust. However, several studies argued against the idea. One argument was that a magma ocean would lose heat very fast because of rapid [convection](#) (fluid motions) inside it, and so freeze. Another argument was that mountains on Io (and there are many) would be destroyed at their bases faster than they could be pushed up. (The formation of nonvolcanic mountains on Io are described in [PSRD](#) article: [Big Mountain, Big Landslide on Jupiter's Moon, Io.](#))

Because of these sound arguments, most recent studies of Io have assumed that the interior is mostly solid. Nevertheless, the idea of a partly molten Io (perhaps up to about 40% molten) was not ruled out. In fact, in 1985, M. Ross and G. Schubert proposed that Io had a partially molten, mushy interior.

Recent observations of Io led Keszthelyi and coworkers to resurrect the notion of a mushy magma ocean inside Io. The most striking observation is that many lavas on Io are quite hot, certainly more than 1200 °C, and possibly as high as 1300 °C. The simplest explanation for such high temperatures is that the lavas are richer in iron and magnesium than normal [basalt](#) lavas like we have on Earth. As planetary interiors melt, the amount of iron and magnesium in the melted portion increases as the amount of melting increases. A temperature as high as 1300 °C implies a high percentage of melting, up to 30% (depending on pressure).

Analysis of the nature of light reflected from Io can give clues to the minerals present. The Galileo team suggests that the color data obtained by the Solid State Imager indicate that the lavas at all of Io's active volcanoes are similar in composition and contain significant amounts of the mineral pyroxene, consistent with high amounts of iron and magnesium. Also, Galileo data show that the distribution of volcanoes on Io is quite uniform, indicating a global source of magma.

We suggest that beneath its solid crust (roughly 100 km thick) Io consists of a sticky slurry of molten rock and suspended crystals. This avoids the problems of a totally molten magma ocean, which would be stirring itself so vigorously by convection that it would cool fast. The mush would not be motionless, however. It would be convecting rapidly enough that the interior (above a metallic core) would be well mixed.



We used a computer program developed by M. S. Ghiorso (University of Washington) and R. O. Sack (Purdue University) to calculate the percentage of solid and molten rock present as a function of depth. Ghiorso and Sack provide the program, called MELTS, to anyone via their web site (see [resource list below](#)). It is used widely by scientists studying rocks formed from magmas. Our calculations show that just below the crust there is a zone in which the amount of melting exceeds 30%. The amount of melting decreases with depth, in spite of the temperature increasing, because higher pressure causes the melting point to increase. The magma ocean is a global, subcrustal region, thus accounting for widespread, hot volcanism all over Io's crust.

The most-melted region would also eat away at the lower crust, partially melting it and mixing it back into the mantle. This prevents the formation of extremely variable rock compositions, which is also consistent with what we know about Io. A mushy mantle would also allow large blocks of the crust to move up and down, as suggested by Paul Schenk of the Lunar and Planetary Institute [see [PSRD article: Big Mountain, Big Landslide on Jupiter's Moon, Io](#)].

Testing the Idea

Current observations of Io are consistent with the idea of a mushy magma ocean in its mantle, but that does not prove the existence of such a magma ocean. Fortunately, there are several tests of the idea.

- One is to determine if hot, iron and magnesium rich lava flows are as common as we suspect. If hot magmas are rare, there is less need for a magma ocean. The Galileo spacecraft carries instruments to identify minerals and other compounds on the surface of Io. Unfortunately, the surface becomes rapidly contaminated with the abundant sulfur gases, such as sulfur dioxide, spewed out by its many volcanoes, so the lava mineralogy is masked. A very young, fresh, uncontaminated flow will be imaged soon, and this might provide more mineralogical information.
- A better estimate for the density of Io's mantle could help us distinguish a solid from a partially molten mantle. A solid mantle would have a density of 3.330 grams per cubic centimeter, while a partially molten one would have a density of 3.270 grams per cubic centimeter. However, such measurements are very tricky. They entail measuring the density of Io and assuming the core is made of a mixture of iron and sulfur. Current estimates of the density of Io's interior range from 3.148 to 3.878 grams per cubic centimeter, though the currently favored value is 3.280, closer to the mushy than to the solid interior.
- If Io has an intrinsic magnetic field, it might favor a solid interior, while the lack of such a field would suggest a mushy interior. Magnetic fields are generated inside convecting metallic cores. If Io had a

magma ocean, the ocean (hence the mantle above the core) would be hotter than the core. This would inhibit motions in the core, and there would be no magnetic field. On the other hand, if the mantle were solid, the core would be able to convect and generate a field. An attempt to measure Io's magnetism failed recently because the spacecraft went into its safe mode during a close approach to Io. Another attempt is planned in early 2001.

- A network of seismometers to monitor Io quakes would be the most definitive test. These would be able to measure the properties of the interior, and clearly distinguish between a solid and a partially molten interior. This test is a long way off!

Magma Oceans Elsewhere

Planetary scientists believe that the Moon had a magma ocean when it formed [see PSRD article: [Moonbeams and Elements](#)] and that the Earth's formation involved so many impacts by huge projectiles that it almost certainly melted as well [see PSRD article: [Origin of the Earth and Moon](#)]. There is some evidence that even some asteroids were so hot when they formed that they had at least mushy magma oceans. If the idea of a mushy magma ocean is correct, we hope that studies of the processes in an active magma ocean on Io will help us understand the now-solidified magma oceans elsewhere. However, the comparisons will not be straightforward. For example, Io is being heated continuously, so it does not allow formation of a crust by the floatation of low-density mineral grains, as happened on the Moon. It is much smaller than the Earth, so the processes operating inside a magma ocean on Io may be simpler than inside Earth. Nevertheless, we are bound to learn something about the complex processes that operate in huge magma systems.

Additional Resources

[Galileo Mission](#)

[Io images and information](#) from the Galileo Mission, presented by the Lunar and Planetary Lab, University of Arizona.

[Io images](#) including 3-D, and a movie, from the Lunar and Planetary Institute.

Keszthelyi, L., McEwen, A. S., and Taylor, G. J. (1999) Revisiting the hypothesis of a mushy global magma ocean on Io. *Icarus*, v. 141, p. 415-419.

Martel, L.M.V. "Big Mountain, Big Landslide on Jupiter's Moon, Io" *PSR Discoveries*. April 1998. <http://www.psr.d.hawaii.edu/April98/io.html>.

[MELTS program](#), software package for modeling crystallization of magmatic systems.

Peale, S. J., Cassen P., and Reynolds, R. T. (1979) Melting of Io by tidal dissipation. *Science*, v. 203, p. 892-894.

Taylor, G. Jeffrey "Moonbeams and Elements" *PSR Discoveries*. October 1997. <http://www.psr.d.hawaii.edu/Oct97/MoonFeO.html>.

Taylor, G. Jeffrey "Origin of the Earth and Moon" *PSR Discoveries*. December 1998. <http://www.psr.d.hawaii.edu/Dec98/OriginEarthMoon.html>.