Waves of lava seen in Io's largest volcanic crater

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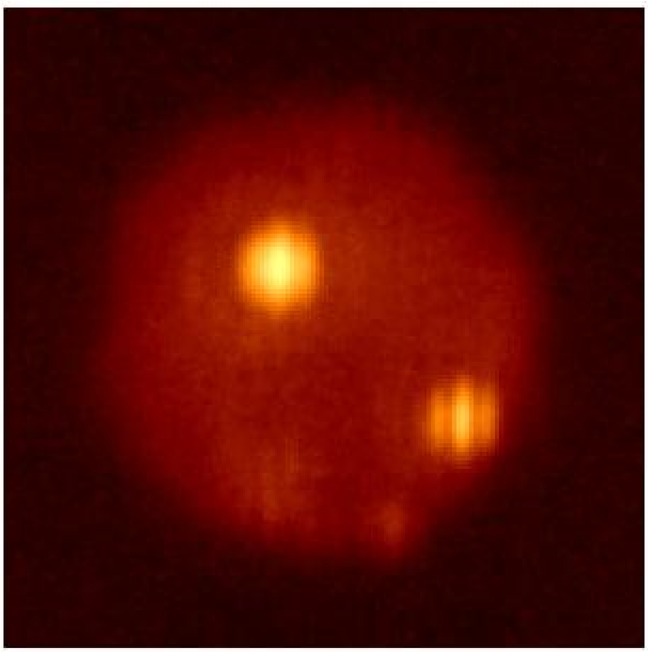


Series of LBTO images showing Europa crossing the disk of Io. Loki Patera is the bright hot spot in the upper part of the disk. Europa appears dark because water ice on its surface absorbs incident sunlight, while the sulfur dioxide ice on Io's surface is less absorbing at this wavelength. Credit: Large Binocular Telescope Observatory

Taking advantage of a rare orbital alignment between two of Jupiter's moons, Io and Europa, researchers have obtained an exceptionally detailed map of the largest lava lake on Io, the most volcanically active body in the solar system.

On March 8, 2015, Europa passed in front of Io, gradually blocking out light from the volcanic moon. Because Europa's surface is coated in water ice, it reflects very little sunlight at infrared wavelengths, allowing researchers to accurately isolate the heat emanating from volcanoes on Io's surface.

The infrared data showed that the surface temperature of Io's massive molten lake steadily increased from one end to the other, suggesting that the lava had overturned in two waves that each swept from west to east at about a kilometer (3,300 feet) per day.

Overturning lava is a popular explanation for the periodic brightening and dimming of the hot spot, called Loki Patera after the Norse god. (A patera is a bowl-shaped volcanic crater.) The most active volcanic site on Io, which itself is the most volcanically active body in the solar system, Loki Patera is about 200 kilometers (127 miles) across. The hot region of the patera has a surface area of 21,500 square kilometers, larger than Lake Ontario.

Earthbound astronomers first noticed Io's changing brightness in the 1970s, but only when the Voyager 1 and 2 spacecraft flew by in 1979 did it become clear that this was because of volcanic eruptions on the surface. Despite highly detailed images from NASA's Galileo mission in the late 1990s and early 2000s, astronomers continue to debate whether the brightenings at Loki Patera - which occur every 400 to 600 days - are due to overturning lava in a massive lave lake, or periodic eruptions that spread lava flows over a large area.

"If Loki Patera is a sea of lava, it encompasses an area more than a million times that of a typical lava lake on Earth," said Katherine de Kleer, a UC Berkeley graduate student and the study's lead author. "In this scenario, portions of cool crust sink, exposing the incandescent magma underneath and causing a brightening in the infrared."

"This is the first useful map of the entire patera," said co-author Ashley Davies, of the Jet Propulsion Laboratory in Pasadena, who has studied Io's volcanoes for many years. "It shows not one but two resurfacing waves sweeping around the patera. This is much more complex than what was previously thought".

"This is a step forward in trying to understand volcanism on Io, which we have been observing for more than 15 years, and in particular the volcanic activity at Loki Patera," said Imke de Pater, a UC Berkeley professor of astronomy.

De Kleer is lead author of a paper reporting the new findings that will be published May 11 in the journal *Nature*.

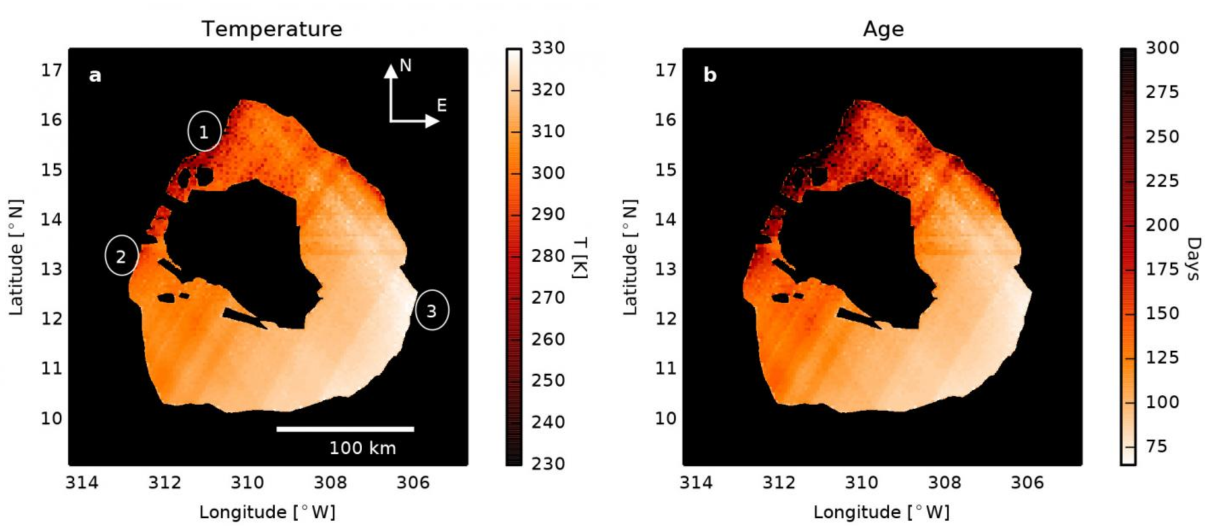
Binocular telescope turns two eyes on Io

The images were obtained by the twin 8.4-meter (27.6-foot) mirrors of the Large Binocular Telescope Observatory in the mountains of southeast Arizona, linked together as an interferometer using advanced adaptive optics to remove atmospheric blurring. The facility is operated by an international consortium headquartered at the University of Arizona in Tucson.

"Two years earlier, the LBTO had provided the first ground-based images of two separate hot spots within Loki Patera, thanks to the unique resolution offered by the interferometric use of LBT, which is equivalent to what a 23-meter (75-foot) telescope would provide," noted co-author and LBTO director Christian Veillet. "This time, however, the exquisite resolution was achieved thanks to the observation of Loki Patera at the time of an occultation by Europa."

Europa took about 10 seconds to completely cover Loki Patera. "There was so much infrared light available that we could slice the observations into one-eighth-second intervals during which the edge of Europa advanced only a few kilometers across Io's surface," said co-author Michael Skrutskie, of the University of Virginia, who led the development of the infrared camera used for this study. "Loki was covered from one direction but revealed from another, just the arrangement needed to make a real map of the distribution of warm surface within the patera."

These observations gave the astronomers a two-dimensional thermal map of Loki Patera with a resolution better than 10 kilometers (6.25 miles), 10 times better than normally possible with the LBT Interferometer at this wavelength (4.5 microns). The temperature map revealed a smooth temperature variation across the surface of the lake, from about 270 Kelvin at the western end, where the overturning appeared to have started, to 330 Kelvin at the southeastern end, where the overturned lava was freshest and hottest.



Maps of the temperature and lava crust age within Loki Patera, derived from the LBTO observations. The higher temperatures in the southeast (location 3) indicate that new magma was exposed most recently in this location. Credit:

Large Binocular Telescope Observatory

Using information on the temperature and cooling rate of magma derived from studies of volcanoes on Earth, de Kleer was able to calculate how recently new magma had been exposed at the surface. The results - between 180 and 230 days before the observations at the western end and 75 days before at the eastern - agree with earlier data on the speed and timing of the overturn.

Interestingly, the overturning started at different times on two sides of a cool island in the center of the lake that has been there ever since Voyager photographed it in 1979.

"The velocity of overturn is also different on the two sides of the island, which may have something to do with the composition of the magma or the amount of dissolved gas in bubbles in the magma," de Kleer said. "There must be differences in the magma supply to the two halves of the patera, and whatever is triggering the start of overturn manages to trigger both halves at nearly the same time but not exactly. These results give us a glimpse into the complex plumbing system under Loki Patera."

Lava lakes like Loki Patera overturn because the cooling surface crust slowly thickens until it becomes denser than the underlying magma and sinks, pulling nearby crust with it in a wave that propagates across the surface. According to de Pater, as the crust breaks apart, magma may spurt up as fire fountains, akin to what has been seen in lava lakes on Earth, but on a smaller scale.

De Kleer and de Pater are eager to observe other Io occultations to verify their findings, but they'll have to wait until the next alignment in 2021. For now, de Kleer is happy that the interferometer linking the two telescopes, the adaptive optics on each and the unique occultation came together as planned that night two years ago.

"We weren't sure that such a complex observation was even going to work," she said, "but we were all surprised and pleased that it did."

More information: Multi-phase volcanic resurfacing at Loki Patera on Io, *Nature* (2017). nature.com/articles/doi:10.1038/nature22339

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