Loki, Io: A periodic volcano

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[1] Loki is the most powerful volcano in the Solar System. It has been observed to be in continuous though variable activity since 1979. Synthesis of more than a decade of groundbased data suggests that Loki eruptions are cyclic, with a 540 day period. Application of a simple lava cooling model to temperatures in Loki Patera, and eruption start and end times, implies that brightenings are due to a resurfacing wave propagating across the patera. The data are most consistent with lava lake overturn, but resurfacing by lava flows cannot be ruled out. A porosity gradient in the lake crust could cause lava lake overturn to occur periodically on the timescale observed. *INDEX TERMS:* 8414 Volcanology: Eruption mechanisms; 6218 Planetology: Solar System Objects: Jovian satellites; 5464 Planetology: Solid Surface Planets: Remote sensing; 5480 Planetology: Solid Surface Planets: Volcanism (8450); 5418 Planetology: Solid Surface Planets: Heat flow

1. Introduction and Groundbased Data

[2] Loki Patera is a 200 km diameter horseshoe-shaped low albedo feature on Io, located at approximately 10 N 310 W. Galileo measurements confirm that the hottest portions are equivalent to the low albedo regions and recent Galileo Photo-polarimeter-Radiometer (PPR) estimates indicate that when active, Loki accounts for roughly 15% of the satellite's heat flow [*Spencer et al.*, 2000]. Its infrared brightness can be measured from the ground by using Jupiter occultations of Io [*Spencer et al.*, 1990]. Combining infrared brightnesses from several sources (Figure 1), including the Galileo Near Infrared Mapping Spectrometer (NIMS), the eruption history of Loki can be traced for well over a decade. At least eight distinct brightening events have been observed since early 1987, with 3.5 μm brightness up to 10 times higher during a brightening than during quiescent periods.

[3] We tested for periodicity in the Loki data using two techniques. We used the Lomb method [*Press et al.*, 1992] for taking a Fourier transform of unevenly sampled data. This yielded a period of 545 ± 15 days to a high significance level: the probability of this peak occurring in a random sample is less than 4×10^{-17}. We also used phase dispersion minimization [*Schleicher et al.*, 1990; *Stellingwerf*, 1978] to test periodicity. This method assumes no shape and wraps the data to various periods, minimizing the scatter of points at each phase. This method yielded a period of 540 ± 10 days with a low probability (less than 10^{-5}) of random occurrence. Figure 2 shows the data wrapped to this period. Brightenings last an average of 230 days, but progress differently. Loki is, however, consistently dim for about 150 days during each cycle.

2. Spacecraft Data

[4] Loki appears to be a silicate volcano. Two-temperature fits to Galileo NIMS Loki data yield high temperature components of greater than 900 K, consistent with silicate lava [*Davies et al.*, 2000]. Further, Loki has been seen at wavelengths less than 1 μm by Galileo SSI [*McEwen et al.*, 1998], also indicative of high temperatures (>700K) and silicate volcanism.

[5] During the 1999/2000 brightening, Galileo's PPR instrument obtained two high-resolution images of Loki, one on October 11, 1999 (I24) and the other on February 20, 2000 (I27). Loki underwent dramatic changes in brightness temperature distribution during this period [*Spencer et al.*, 2000], with the hottest area moving from the southwest corner of the patera to the eastern portion of the patera (note: subsequently, we will assume unit emissivity, and thus substitute "temperature" for "brightness temperature").

[6] The PPR temperature distributions are consistent with a model in which a wave of resurfacing by silicate magma propagated around the Loki patera during the 1999–2000 Loki brightening, starting in the southwest corner [*Spencer et al.*, 2000]. To demonstrate this, we use the analytic lava cooling model [*Howell*, 1997] which treats radiative cooling and freezing of a semi-infinite half space of silicate lava with a porosity of 5%, initially at its melting point. This model has previously been used to model the 1999–2000 Loki brightening [*Howell et al.*, 2001], showing that the model derived eruption rate based on groundbased data at 3.39, 4.8, and 8.7 μm was consistent with changes in areal coverages determined from the PPR data. We adapt this model to higher porosities by changing the thermal conductivity using the formulation of *Keszthelyi and Denlinger* [1996].

[7] The highest resolution portion of the I24 image (Figure 3) shows two areas of uniform, but not equal, brightness, separated by a small, linear region of higher brightness temperature, assumed to be the eastward-propagating resurfacing front. The hotter region, at 330 K, we propose was resurfaced earlier in the 1999 brightening, which began sometime between August 25 and September 9, 1999 [*Howell et al.*, 2001], 32–47 days before the observation. If resurfacing started in the southwest corner, a propagation speed of about 2 km/day for the resurfacing front is inferred from its location in I24, 80 km from the western margin. The cooler eastern region, at 250 K in I24, we propose was resurfaced near the end of the previous brightening, which ended between December 31, 1998 and January 23, 1999, 261–284 days before I24 (Figure 1). In I27, the temperature of the eastern part of the patera had increased to 290 K. If the resurfacing front continued to propagate at 2 km/day after I24, it would have reached reached the warmest I27 region (about 100 km away) about 50 days after I24, or about 82 days before I27. Continuing at this speed, the resurfacing would have covered the entire patera (about 400 km around to the northwest corner) in about 200 days, approximately the same amount of time an average brightening lasts. The temperatures calculated based on the above ages are shown in Table 1. A lava porosity of about 10% gives a good match to the observed temperatures, supporting the model.

[8] Voyager images may have been taken during a similar brightening in 1979. The 4.8 μm vertical emission from Loki at

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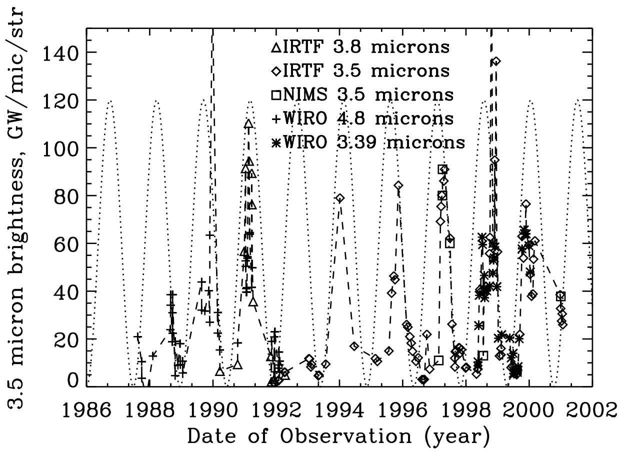

Figure 1. 3.5 μm brightness of Loki as measured primarily from Jupiter occultations. Some of the data was taken at other wavelengths (3.8, 4.8 and 3.39 μm). The 4.8 μm data were translated to 3.5 μm assuming a color temperature of 355 K [*Spencer et al.*, 1992]. The 3.39 μm data were translated to 3.5 μm using a color temperature found to be 500 K by equating data taken at both wavelengths at the same time. Similarly for the 3.5 to 3.8 μm color temperature of 500K. Also included are 3.5 μm measurements from Galileo NIMS observations that resolve Loki. The dotted sine wave has a period of 540 days to show the periodicity of Loki's brightenings.

Voyager 1 was 90 GW/μm/str [*Pearl and Sinton*, 1982], about 2.5 times greater than the 4.8 μm brightness measured from the ground during "off" times and 3 times less than the peak brightness, consistent with the observation being near the start of a brightening. Voyager 1 and Voyager 2 images of Loki also show apparent resurfacing propagating across Loki and originating in the south-west corner. A Voyager 1 image taken in March 1979 in the blue filter (Figure 4a) is the highest resolution image of Loki available and shows a lower albedo region in the extreme south-west corner of Loki. A Voyager 2 image taken in July 1979 (Figure 4b) shows a lower albedo region extending over most of the southern portion of Loki. These images together suggest a resurfacing wave of dark material which begins in the south-west corner and propagates counter-clockwise, similar to the hot areas in the 1999–2000 brightening, and propagating at a speed of approximately one kilometer per day. We believe that in the Voyager case the resurfacing wave is visible because the Loki plume was active

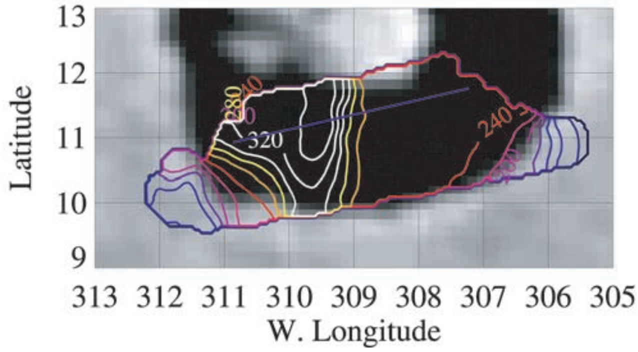

Figure 3. High-resolution portion of PPR 17-μm brightness temperature map of Loki taken October 11, 1999 (I24), superimposed on a Galileo visible-wavelength image. The contour interval is 20 K. PPR resolution is approximately 0.6 deg (20 km).

[*Smith et al.*, 1979]. A general increase in albedo in this area occurred between Voyager 1 and Voyager 2, possibly the result of pyroclastic deposition from the plume [*Smith et al.*, 1979] and consistent with the idea that the darker material is freshly resurfaced.

[9] There are two other pieces of intriguing evidence of discrete, mobile, hot regions within the Loki patera which deserve mention. First, mutual satellite occultation data taken during the 1991 Loki brightening [*Goguen et al.*, 1993] clearly show two high-temperature emitting regions separated by 100 km, probably both within the patera. This observation indicates that some brightenings involve more than a single propagating hot region. Second, SSI detected thermal emission from two significantly different locations within Loki in E6 (2/21/97) near the start of a brightening and C9 (6/28/97) in the middle of a brightening [*McEwen et al.*, 1998].

3. Models

[10] We now consider two models for the periodic propagating resurfacing waves that we infer from the data: lava flows and lava lake overturn.

3.1. Lava Flows

[11] Resurfacing could be accomplished by eruption of a source vent in the southwest corner of Loki, with flows covering the patera floor. However, the I27 PPR images show no enhanced emission at this presumed vent location [*Spencer et al.*, 2000]. In contrast, NIMS images of Io's Prometheus and Amirani lava flows

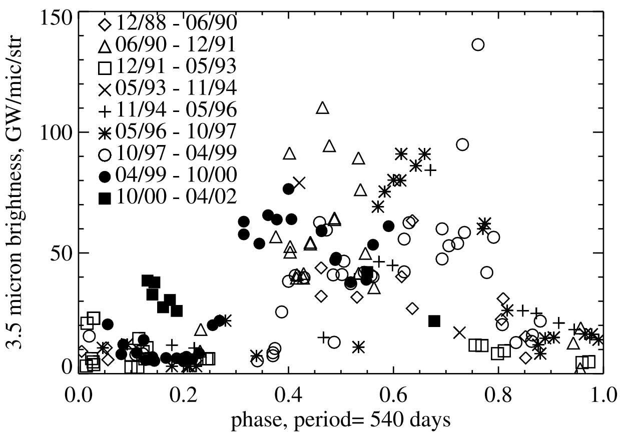

Figure 2. 3.5 μm brightness of Loki (Figure 1) wrapped to a period of 540 days. The symbols indicate the cycle.

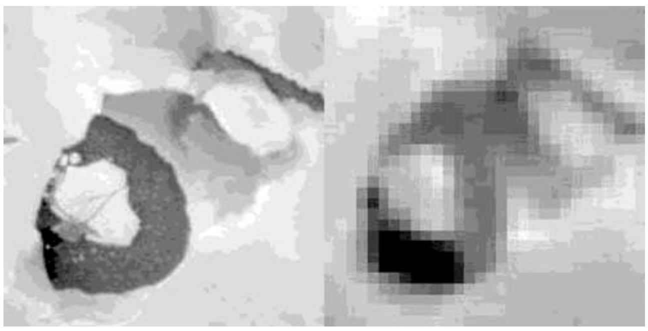

Figure 4. (a) Voyager 1 image of Loki taken March 1979. Note the lower albedo region in the extreme south-west corner. (b) Lower-resolution Voyager 2 image of Loki taken July 1979. Note the much larger low albedo region.

Table 1. Cooling Model Derived Temperatures, K, of Basaltic Lava Within Loki Calculated From Ages Determined in the Text

Region	West in I24	East in I27	East in I24
		Assumed age of lava (days)	
Porosity	39 ± 8	82	271 ± 10
5%	340 ± 8	310	267 ± 2
10%	327 ± 8	298	257 ± 2
20%	302 ± 8	275	237 ± 1
Observed	330	290	250

generally show emission not only from a spot at the flow front but also from the vent that is the primary magma source [*Lopes-Gautier et al.*, 2000].

[12] If resurfacing is by lava flows, we can estimate the total thickness of flows since Voyager. Since the cooling model of *Howell* [1997], which assumes cooling of a semi-infinite half space, is consistent with observations, the lava flow must be as least as thick as the depth to which the cooling wave has propagated. The longest timescale involved is approximately 300 days, by which the cooling wave has reached about 5–10 meters depth [*Turcotte and Schubert*, 1982]. If eruptions occur once every 540 days, then 14 eruptions have occurred since Voyager 1 in March 1979. The overlapping flows would be about 70–140 m thick, and the patera walls would have to be higher than this to prevent overflow. The calculated minimum flow thickness and the surface creation rate, 1160 m^2 s^{-1} [*Howell et al.*, 2001], give a minimum eruption rate of 8120 m^3 s^{-1}.

[13] Most current terrestrial basaltic lavas have effusion rates of several to tens of cubic meters per second [*Wadge*, 1981], but effusion rates up to several thousand m^3 s^{-1} have been postulated in the geologic past [*Reidel*, 1998; *Keszthelyi and Self*, 1998; *Thordarson and Self*, 1998], and even current eruptions can approach the Loki minimum effusion rates at the start of an eruption. Eruptions rates of other Ionian volcanoes have been estimated at several tens to thousands of m^3 s^{-1} [*Davies et al.*, 2001]. The consistency of the lava cooling model with all the 1999–2000 observations suggests that Loki exhibits a constant high eruption rate, unlike terrestrial lava flows. Terrestrial lava flows are not periodic, even when they are highly episodic, and the time scales of the episodes are much shorter (e.g., on order a few days during the early stages of the Pu'u O'o eruption at Kilauea [*Wolfe et al.*, 1988]) than the 540 day period of Loki.

3.2. Lava Lake Overturn

[14] Another possibility for Loki eruptions is propagating lava lake overturn. Some terrestrial lava lakes, though more than two orders of magnitude smaller, overturn in a way that would yield thermal signatures similar to those seen by PPR. Makaopuhi, on Kilauea in Hawaii, overturned repeatedly in 1965 [*Turcotte*, 1995; *Wright et al.*, 1968]. Crustal foundering began at a point or line near the margin of the lake and propagated away from the point of origin [*Wright et al.*, 1968]. At the origin, a crack would form and a block of crust would founder and sink, followed by the neighboring block, propagating coherently across the lake, just as we see at Loki. Crack initiation is readily accomplished by thermal contraction of the crust. The temperature difference needed is given by $\Delta T = \sigma/\alpha E$, where σ is the unconfined tensile strength (about 10 MPa), α is the linear expansion coefficient, and E is Young's modulus (50 GPa), yielding ΔT of only 18.2 K. Small rafts of less dense crust occasionally escaped the resurfacing at Makaopuhi. The Voyager 1 image (Figure 4a) shows small, high-albedo spots in the patera which could be rafts that escaped overturn, are older and therefore brighter due to plume fallout. These features are the same in general appearance as the larger high albedo angular features in the center and northwest edge of the patera. Further, Loki's appearance and thermal signature is unique, suggesting it forms by a different mechanism from other Ionian volcanoes, which predominantly involve flows [*McEwen et al.*, 1998]. While Loki is the largest and most powerful volcano on Io, it appears faint at short wavelengths [*McEwen et al.*, 1998] implying that the resurfacing mechanism exposes much less high-temperature magma than other, smaller, Ionian volcanos. The periodic behavior and apparent "rafts" are also unique. If Loki is overturning, perhaps the two hot areas seen in the 1991 mutual event data [*Goguen et al.*, 1993] are two different areas overturning simultaneously.

[15] A lava lake could overturn periodically if the right conditions were met. The solidified crust on the lake would have to be stable when it formed but become unstable as it thickened and cooled. Stability could change due to thermal contraction alone. In a typical terrestrial basalt, the density of the solidified crust, 2800 kg m^{-3}, is already significantly higher than the density of the underlying liquid, 2600 kg m^{-3}. Porosity in the crust could make the crust initially stable. As it cooled, its density could then increase until it became unstable. If we use the volume expansion coefficient of basalt, 32×10^{-6} K^{-1} [*Washburn*, 1926–1933], and assume that the crust's surface temperature decreases from 1250 K to the 250 K observed in the PPR images, the corresponding increase in density is 45 kg m^{-3} for no porosity, assuming that the temperature in the solid crust increases linearly with depth. For a molten lava porosity of 0% the solidified crust must have an average porosity of about 8.6% and for molten lava with a porosity of 10%, the crustal porosity must be about 18% for overturn to occur at observed timescales.

[16] Additionally, mean crust porosity could decrease with time. Porosities in terrestrial lava lakes can be measured once the lake has solidified [*Peck et al.*, 1966]. Measurements for two Hawaiian lakes [*Wright et al.*, 1976] show surface porosities of about 40%, decreasing almost exponentially to about 10% at depth [*Peck et al.*, 1966]. A crust with a porosity of 40% has a density of only 1730 kg m^{-3} and is buoyant at any temperature. However, the addition of less porous material to the base of the crust during freezing could eventually make it dense enough to be unstable. Using the Hawaiian measured porosities and including crustal cooling, solid crust would become gravitationally unstable at a depth of about 6 meters if the underlying liquid has 10% bubbles. Earlier, we used the cooling-model derived age of 300 days to find a minimum crustal thickness of about 5–10 meters, remarkably similar considering the uncertainties involved. We have shown that the increasing density of a thickening crust, due to thermal contraction perhaps aided by decreasing mean porosity, can cause the crust to overturn on the observed timescales.

4. Conclusions

[17] We favor the interpretation of Loki as a lava lake overturning when the solid crust becomes too dense. To accomplish this, the crust must have a greater porosity than the underlying liquid. The lack of a hot area at the likely flow source in the February 2000 PPR image and the overall uniqueness of Loki's appearance and thermal signature support this interpretation. If Loki is a lava lake, it is intermediate in size and timescale between terrestrial lava lakes and global plate tectonics and may have implications for possible episodic Venusian lithospheric overturn *Turcotte* [1995].

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