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# Io's Loki Patera: Modeling of three brightening events in 2013–2016

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ABSTRACT

Loki Patera is one of the most dramatically time-variable volcanic features on Io, exhibiting episodic brightening events every 1–3 years that may produce over 15% of Io's global heat flow. We observed three such brightening events with adaptive optics imaging at the Keck and Gemini N telescopes over the course of 70 nights of observation in 2013–2016. The high cadence and multi-wavelength nature of the observations provides constraints on models for activity at Loki Patera. The Matson et al. (2006) model for Loki Patera as an overturning basaltic magma sea is adapted to fit the observations of all three events. In particular, we adjust the details of the overturn progression, and modify the lava thermal properties to include dependencies on temperature and porosity, to improve the fit to the data. The preferred models find overturn front propagation velocities of 1.2–1.7 km/day, corresponding to resurfacing rates of 1500–2200 $m^2$/s. The time intervals of 440–540 days between successive events are roughly consistent with the 540-day period calculated by Rathbun et al. (2002) for events prior to 2001. The best coverage was obtained for the 2016 brightening; model fits to this event require a lava bulk thermal conductivity of 0.55–0.75 W/m/K, with the best fit obtained for a value of ~0.7 W/m/K and an average porosity that decreases during cooling. For all three events, the overturn front appears to propagate around the patera in the clockwise direction, opposite to what has been inferred for past brightening events. There is evidence that the overturn may be more complex than a single propagating wave, perhaps involving multiple simultaneous resurfacing waves as well as portions of the patera that are active even after the nominal bright phase has ended. The measured intensities are anomalously low when Loki Patera is viewed at high emission angles, suggestive of topographic shadowing due to a raised area or the edge of the depression in which the magma sea resides.



## 1. Introduction

One of the most distinctive and well-studied volcanic features on Io, Loki Patera is a large low-albedo region approximately 2.15 $\times$ $10^4$ $km^2$ in area and roughly annular in shape. Its size and consistently-present activity during the 37 years since its discovery by *Voyager* (Smith et al., 1979) make it an ideal observational target for studying volcanic processes on Io. Its immense heat flow constitutes 10–15% of the total time-averaged heat flow from Io (Veeder et al., 1994; Spencer et al., 2000); understanding how Io's heat is released globally therefore requires an understanding of this unusual volcanic feature.

After its discovery by *Voyager* (Smith et al., 1979), Loki Patera was observed in detail by *Galileo* (e.g. Lopes-Gautier et al., 1999; Spencer et al., 2000; Turtle et al., 2004) and from the ground via occultations by Jupiter (e.g. Spencer et al., 1990). With adaptive optics on large near-infrared telescopes, the emission from individual volcanoes on Io can be distinguished (Marchis et al., 2005), Loki Patera's 1–5 μm intensity can be measured, and the location of the primary source of emission within the patera can be constrained (de Pater et al., 2014b; 2017). Recently, the Large Binocular Telescope Interferometer (LBTI) resolved emission from Loki Patera for the first time from the ground with near-infrared Fizeau imaging, detecting emission from two distinct locations within the southern part of the patera (Conrad et al., 2015).

Shortly after its discovery, Loki Patera was noted to brighten every 1–3 years, involving a rapid increase of intensity followed by months of high activity before fading (Howell and Sinton, 1989; Spencer et al., 1994). Based on *Galileo* photopolarimeter-radiometer (PPR) observations during the I24 and I27 flybys, Spencer et al. (2000) suggested that the hottest area within Loki Patera could represent a flow front or lava lake overturn front, and early brightening models treated Loki Patera as a spreading lava flow

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(Carr, 1986; Davies, 1996; Howell et al., 2001). From a synthesis of 3.5–4.0 μm measurements of eight distinct brightening events between 1987 and 2002, Rathbun et al. (2002) derived a periodicity of 540 days for the brightenings and proposed a model in which Loki Patera is an active lava lake with a resurfacing wave that propagates across the surface (though they could not rule out resurfacing by lava flows). In this model, overturn is triggered when the solid crust that forms on the surface of the lake becomes denser than the underlying magma; the time it takes for this to occur may vary between brightenings based on variable magma properties such as volatile content. This model was adapted to interpret *Galileo* high-resolution observations (Davies, 2003) and expanded by Rathbun and Spencer (2006) to explain an apparent "turning off" of the activity after 2001. Matson et al. (2006) built on these models, adding an analysis of the volatile content of the magma to develop a self-consistent and physically-motivated model of Loki Patera as an overturning magma sea. After 2001, no major activity was detected at Loki Patera until 2009, after which five additional brightening events were seen (de Pater et al., 2011, 2017).

We observed the three events that took place between 2013 and 2016 with near-infrared (2–5 μm) adaptive optics imaging at the Keck and Gemini N telescopes on 70 nights during this period. The high-cadence and multi-wavelength nature of these observations yields unprecedented constraints on models for volcanism at Loki Patera, and are used here to refine the Matson et al. (2006) magma sea model. Section 2 describes the observations. In Section 3, the original magma sea model is summarized, and our modifications to the model are discussed in detail. An analysis of the fits for a variety of model choices is presented in Section 4, and the implications of these results are discussed in Section 5. Section 5.3 focuses on evidence for a topographic feature blocking emission at high viewing angles. The conclusions are summarized in Section 6.

## 2. Observations

Observations of Loki Patera in the near-infrared were made with adaptive optics at the Keck and Gemini N telescopes between August 2013 and June 2016, on 17 and 53 nights for the two telescopes respectively. The Keck observations use the NIRC2 imager with a platescale of 9.94 ± 0.03 mas/pixel (de Pater et al., 2006), or 30–45 km on Io's surface at disk center depending on the Earth-Io distance. Data are obtained in a range of filters from H-cont (1.6 μm) out to Ms (4.7 μm). At Gemini N the NIRI instrument is used to image Io in the L-prime and K-cont filters (3.78 and 2.27 μm respectively) at a platescale of 0.022"/pixel. Emission from Loki Patera is typically only seen at wavelengths longer than 3 μm. Emission at shorter wavelengths is detected primarily during the peak of brightening episodes.

These observations were obtained as part of a high-cadence, high-spatial-resolution Io imaging campaign (de Kleer et al., 2014; de Kleer and de Pater, 2016). This article focuses exclusively on an analysis of the observations of Loki Patera; the observing and data reduction procedures, including the extraction of hot spot intensities and positions, are described in de Kleer and de Pater (2016) where the results of the full program are presented, and in de Pater et al. (2017). The details of all observations, as well as the measured intensities and positions, are summarized in Table 1.

## 3. Overturning magma sea model

The time evolution of Loki Patera's near-infrared intensity during and after brightening events places important constraints on the nature of its volcanic activity. This analysis uses a model based on the Matson et al. (2006) model of Loki Patera as an overturning magma sea of basaltic composition, to which modifications are made to improve the fit to the data. In addition, the thermal properties of the lava are adapted to include dependencies on temperature and porosity according to models for volcanism on Earth (Keszthelyi and Delinger, 1996; Patrick et al., 2004). The analysis treats Loki Patera as an overturning magma sea; alternate mechanisms such as resurfacing by lava flows have not been ruled out, although previous authors have found the foundering crust mechanism to match the observed properties better (Rathbun et al., 2002; Matson et al., 2006). Alternative models for activity at this volcanic site are discussed in Section 5.4.

The model consists of (1) a thermochemical cooling model for basalt (Section 3.1); (2) a model for the overturn, including geometry of the lake and propagation of the overturn front (Section 3.2); and (3) a model for the thermal properties of the lava, as a function of temperature and porosity when relevant (Section 3.3). Two variants of the lava thermal properties are used in the analysis: the fixed properties used by Matson et al. (2006; *Standard Model*), and a *Modified Model* in which thermal properties depend on temperature and porosity. In the Matson et al. (2006) model, the average porosity of the crust decreases as the crust thickens, and overturn is triggered when this system becomes gravitationally unstable. We implicitly assume this mechanism for overturn triggering, although our data do not provide new insight into the triggering mechanism and we thus do not directly treat this aspect of the model.

### *3.1. Basaltic cooling model*

The magma sea model treats Loki Patera as a semi-infinite lava reservoir of basaltic composition. It calculates the crust thickness and surface temperature as a function of time, including the effect of latent heat released as the crust solidifies, according to the method described by Turcotte and Schubert (1982), which was used by Head and Wilson (1986) to model Venusian lavas, and applied to Io by Davies (1996).

The model is formulated on the assumptions that the magma remains continuously molten beneath a surface crust layer, and that the magma is deep enough that boundary conditions at the bottom of the lake do not affect the observed emission. As an area of crust founders, a section of hot magma becomes newly exposed to the environment. As this new magma cools, a new crust forms and thickens on the surface. Magma in contact with the base of the crust solidifies onto the crust, releasing latent heat that is then conducted through the crust layer and released in the form of radiation. The radiative intensity is given by the Stefan–Boltzmann law:

$$F_{rad} = \sigma\epsilon(T_{surf}^4 - T_{env}^4) \; [\mathrm{W/m^2}] \tag{1}$$

where $T_{env}$ is taken as zero for Io, $\epsilon$ is the thermal emissivity, and $\sigma$ is the Stefan–Boltzmann constant. The latent heat released at the crust-magma boundary is (Turcotte and Schubert, 1982)

$$Q = \rho L \frac{dC}{dt} \; [\mathrm{W/m^2}] \tag{2}$$

where $\rho$ is the density (kg/m$^3$), $L$ is the latent heat (J/kg), and $C$ is the thickness of the crust in meters. This heat is conducted upward according to Fourier's Law:

$$F_{cond} = k\left(\frac{\delta T}{\delta z}\right)_{z=C} \tag{3}$$

where $z$ is the vertical coordinate, increasing with depth from a value of $z = 0$ at the surface.

Using Eqs. (2) and (3), and given a surface temperature $T_{surf}$, the proportionality constant $\lambda_1$ between the thickness of the crust and the thermal diffusion lengthscale is solved for (Turcotte and Schubert, 1982):

$$\lambda_1 = \frac{C(t)}{2\sqrt{\kappa t}}, \tag{4}$$