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 m²/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 brightening 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 2.15×10^4 km² 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 μ m 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).

16 Shortly after its discovery, Loki Patera was noted to brighten every 1-3 years, involving a rapid increase of
17 intensity followed by months of high activity before fading (Howell and Sinton, 1989; Spencer et al., 1994). Based
18 on *Galileo* photopolarimeter-radiometer (PPR) observations during the I24 and I27 flybys, Spencer et al. (2000)
19 suggested that the hottest area within Loki Patera could represent a flow front or lava lake overturn front, and
20 early brightening models treated Loki Patera as a spreading lava flow (Carr 1986; Davies 1996; Howell et al.,
21 2001). From a synthesis of 3.5-4.0 μm measurements of eight distinct brightening events between 1987 and 2002,
22 Rathbun et al. (2002) derived a periodicity of 540 days for the brightenings and proposed a model in which Loki
23 Patera is an active lava lake with a resurfacing wave that propagates across the surface (though they could not rule
24 out resurfacing by lava flows). In this model, overturn is triggered when the solid crust that forms on the surface
25 of the lake becomes denser than the underlying magma; the time it takes for this to occur may vary between
26 brightenings based on variable magma properties such as volatile content. This model was adapted to interpret
27 *Galileo* high-resolution observations (Davies, 2003) and expanded by Rathbun and Spencer (2006) to explain an
28 apparent “turning off” of the activity after 2001. Matson et al. (2006) built on these models, adding an analysis
29 of the volatile content of the magma to develop a self-consistent and physically-motivated model of Loki Patera
30 as an overturning magma sea. After 2001, no major activity was detected at Loki Patera until 2009, after which
31 five additional brightening events were seen (de Pater et al. 2011; 2017).

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

2 2. Observations

3 Observations of Loki Patera in the near-infrared were made with adaptive optics at the Keck and Gemini N
4 telescopes between August 2013 and June 2016, on 17 and 53 nights for the two telescopes respectively. The Keck
5 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
6 Io’s surface at disk center depending on the Earth-Io distance. Data are obtained in a range of filters from H-cont
7 (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
8 filters (3.78 and 2.27 μm respectively) at a platescale of $0.022''$ /pixel. Emission from Loki Patera is typically only
9 seen at wavelengths longer than 3 μm . Emission at shorter wavelengths is detected primarily during the peak of
10 brightening episodes.

1 These observations were obtained as part of an high-cadence, high-spatial-resolution Io imaging campaign (de

2 Kleer et al., 2014; de Kleer and de Pater, 2016). This article focuses exclusively on an analysis of the observations
 3 of Loki Patera; the observing and data reduction procedures, including the extraction of intensities and positions,
 4 are described in de Kleer and de Pater (2016) where the results of the full program are presented, and in de Pater
 5 et al. (2017). The details of all observations, as well as the measured intensities and positions, are summarized in
 6 Table 1.

Table 1: Observations and Measured Intensities

UT Date	Telescope ^a	CML ^b	Latitude [°N]	Longitude [°W]	θ^c	$F_{2.3\mu m}^d$ [GW/ $\mu m/sr$]	$F_{3.8\mu m}^d$ [GW/ $\mu m/sr$]	$F_{4.7\mu m}^d$ [GW/ $\mu m/sr$]
08-15-13 ^e	Keck	338°	10.8±1.2	308.8±1.2	29°	7.7±1.4	60±10	
08-20-13	Keck	275°	12.0±0.7	307.9±0.7	33°	13.0±3.3	133±27	200±33
08-22-13	Keck	320°	11.0±0.7	307.8±0.7	13°	7.5±1.3	136±20	205±34
08-29-13	Gemini N	305°	11.4±1.4	307.2±1.5	11°		126±19	
09-03-13	Gemini N	241°	10.9±1.5	308.5±4.8	67°		50±14	
09-05-13	Gemini N	285°	11.3±1.4	307.4±1.7	24°		73±11	
09-07-13	Gemini N	334°	12.0±1.4	307.1±1.7	29°		84±13	
09-09-13	Gemini N	24°	10.3±1.5	310±5	74°		37±19	
09-10-13	Gemini N	226°	12.1±1.5	295±5	69°		14.8±4.6	
11-18-13	Keck	221°	14.3±0.5	309.5±3.7	83°			28±10
11-27-13	Gemini N	257°	11.9±1.5	307.0±2.6	50°		12.0±1.8	
11-29-13	Gemini N	307°	12.5±1.1	306.6±1.1	12°		12.6±1.9	
12-06-13	Gemini N	273°	12.0±1.1	307.5±1.5	36°		10.5±1.6	
12-15-13	Gemini N	320°	12.5±1.1	307.3±1.2	18°		11.2±1.7	
01-20-14	Keck	34°	12.3±0.7	312.6±2.9	75°			17.4±3.8
02-08-14	Keck	274°	10.1±1.0	310.6±0.5	38°		8.5±1.3	24.7±3.8
02-10-14	Keck	318°	10.9±0.6	310.1±0.3	13°		11.1±1.7	31.8±4.8
03-10-14	Gemini N	257°	12.2±1.3	314.0±2.7	57°		6.4±3.2	
03-12-14	Gemini N	302°	12.0±1.2	311.3±1.3	14°		7.7±1.1	
03-28-14	Gemini N	337°	13.1±1.3	309.6±1.6	30°		7.6±1.1	
10-03-14	Gemini N	307°	12.2±1.5	306.9±1.5	12°		127±19	
10-10-14	Gemini N	290°	11.7±1.5	306.7±1.6	19°		128±19	
10-24-14	Gemini N	258°	10.8±1.4	304.8±2.4	47°		66±10	
10-30-14	Keck	39°	11.1±0.6	310.0±4.9	86°		40±28	43±25
10-31-14	Keck	241°	11.2±1.0	302.1±1.0	63°		78±12	155±23
11-25-14	Gemini N	284°	10.7±1.3	307.0±1.5	25°		55±8	
11-27-14	Gemini N	334°	11.1±1.3	305.7±1.6	30°		54±8	
11-29-14	Gemini N	22°	9.4±1.2	299±8	83°		59±31	
11-30-14	Gemini N	228°	9.8±1.3	293.1±3.8	65°		10.5±2.5	
12-02-14	Keck	275°	9.7±1.4	305.2±0.7	32°		47±7	122±18
12-06-14	Gemini N	329°	11.8±1.2	306.1±1.4	25°		29.0±4.3	
12-09-14	Gemini N	249°	10.7±1.3	303.4±2.7	54°		24.1±3.8	
12-16-14	Gemini N	247°	11.2±1.2	305.1±2.8	58°		14.0±2.9	
12-18-14	Gemini N	293°	12.0±1.2	306.5±1.3	17°		24.0±3.6	

01-10-15	Gemini N	296°	12.9±1.1	307.2±1.2	17°		12.4±1.9	
01-12-15	Keck	338°	11.8±0.8	306.7±1.6	35°		23.2±3.5	66±10
01-14-15	Gemini N	327°	12.4±1.1	307.5±1.3	23°		18.7±2.8	
01-26-15	Gemini N	249°	11.7±1.2	307.6±2.8	58°		7.7±3.9	
03-29-15	Gemini N	244°	12.8±1.2	311.7±4.2	68°		11±5	
03-31-15	Keck	291°	12.3±0.8	311.8±0.6	23°		9.8±1.5	29.8±4.5
04-02-15	Keck	339°	12.9±0.9	310.4±0.4	30°		9.3±1.4	28.3±4.2
04-04-15	Keck	25°	12.9±0.9	310.4±0.4	65°			15.4±2.3
04-05-15	Gemini N	250°	12.0±1.2	307.1±2.7	57°		6.0±3.0	
04-09-15	Gemini N	322°	12.4±1.2	311.8±1.3	16°		8.7±1.3	
11-23-15	Keck	327°	12.0±0.6	307.5±1.5	22°		2.9±0.4	13.4±2.0
12-25-15	Keck	328°	14.9±0.7	305.7±1.2	27°	1.1±0.2	38±6	85±13
01-22-16	Keck	277°	13.6±0.4	305.7±0.6	33°	7.4±1.1	147±22	205±30
02-09-16	Gemini N	323°	13.3±1.2	305.3±1.3	22°		94±12	
02-16-16	Gemini N	299°	12.8±1.2	306.4±1.2	14°		72±12	
02-18-16	Gemini N	18°	13.4±1.3	307.1±4.0	71°		60±20	
02-21-16	Gemini N	257°	12.1±1.2	302.7±1.9	46°		43±8	
02-23-16	Gemini N	296°	11.5±1.2	305.6±1.2	14°		63±12	
03-12-16	Gemini N	336°	12.6±1.2	307.9±1.4	31°		75±14	
03-14-16	Gemini N	27°	10.6±1.3	313.9±4.3	74°		31±13	
05-02-16	Gemini N	250°	13.2±1.3	307.7±2.9	57°		16.4±3.4	
05-04-16	Gemini N	299°	14.1±1.3	314.2±1.4	20°		25.9±4.9	
05-09-16	Gemini N	238°	12.0±1.5	313±8	75°		14±8	
05-11-16	Gemini N	281°	14.1±1.3	309.1±1.7	31°		17.8±3.4	
05-13-16	Gemini N	343°	12.3±1.3	308.6±1.7	36°		20.1±3.8	
05-18-16	Gemini N	264°	13.0±1.4	312.3±2.4	49°		19.7±3.8	
05-20-16	Gemini N	314°	12.8±1.3	311.4±1.3	13°		21.9±4.1	
05-25-16	Gemini N	261°	12.5±1.4	311.1±2.5	50°		15.9±3.1	
05-27-16	Gemini N	299°	13.7±1.4	311.4±1.5	18°		20.7±3.9	
06-01-16	Gemini N	234°	11.7±1.2	314.1±5.1	80°		12±8	
06-03-16	Gemini N	281°	14.2±1.4	308.8±1.8	30°		13.9±2.6	
06-05-16	Gemini N	329°	12.5±1.4	311.5±1.5	21°		15.3±2.9	
06-10-16	Gemini N	264°	14.2±1.4	306.4±2.3	44°		8.5±1.6	
06-12-16	Gemini N	314°	11.1±1.4	310.7±1.4	11°		14.0±2.6	
06-17-16	Gemini N	249°	13.1±1.5	308.9±3.7	60°		11.3±2.5	
06-19-16	Gemini N	297°	13.6±1.5	310.8±1.6	19°		12.1±2.3	

^a Further information on the Keck observations is given in de Pater et al. (2017), which includes locations and intensities at additional wavelengths.

^b Central Meridian Longitude from JPL Horizons: <http://ssd.jpl.nasa.gov/horizons.cgi>.

^c Emission angle for Loki Patera.

^d Intensities are taken from de Pater et al. (2014a) for 08-15-13 through 08-20-13; from de Kleer et al. (2014) for 08-29-13 through 09-10-13; and from de Kleer and de Pater (2016a) for 11-18-13 through 12-25-15.

^e Intensities on this date are poorly constrained (see de Pater et al. 2014a for details), and are shown here for completeness but

14 are not included in the plots or analysis.

15 **3. Overturning magma sea model**

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

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

34 *3.1. Basaltic Cooling Model*

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

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

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

4 where T_{env} is taken as zero for Io, ϵ is the thermal emissivity, and σ is the Stefan-Boltzmann constant. The latent
5 heat released at the crust-magma boundary is (Turcotte and Schubert, 1982)

$$Q = \rho L \frac{dC}{dt} \text{ [W/m}^2\text{]} \quad (2)$$

6 where ρ is the density (kg/m³), L is the latent heat (J/kg), and C is the thickness of the crust in meters. This
7 heat is conducted upward according to Fourier's Law:

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

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

9 Using Equations 2 and 3, and given a surface temperature T_{surf} , the proportionality constant λ_1 between the
10 thickness of the crust and the thermal diffusion lengthscale is solved for (Turcotte and Schubert, 1982):

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

11 assuming a thermal diffusivity κ .

12 This then yields the crust thickness as a function of time. The energy radiated into space is equal to the heat
13 conducted from the crust-magma interface to the surface, given by (Turcotte and Schubert, 1982)

$$F_{rad} = F_{cond,z=0} = k \left(\frac{\delta T}{\delta z} \right)_{z=0} = k \frac{T_{z=C} - T_{z=0}}{\sqrt{\pi \kappa t} \operatorname{erf}(\lambda_1)}, \quad (5)$$

14 which is the standard solution to the 1D diffusion equation evaluated at the surface boundary, adjusted by the
15 value of the error function evaluated at λ_1 . The release of latent heat slows the rate of cooling and of crust
16 thickening compared to a case where no phase change occurs. The precise method of solution is described in detail
17 by previous authors (e.g. Turcotte and Schubert, 1982; Head and Wilson, 1986).

18 Figure 1 shows the temperature, 3.8- μ m intensity, and crust thickness as a function of time for basaltic and
19 ultramafic models with fixed thermal properties, as well as a basaltic composition model modified as described in
20 Section 3.3.

21 3.2. Overturn Model

22 The shape of Loki Patera is approximated as an ellipse with a total overturning area of 21,500 km² and
23 dimensions (semi-major and semi-minor axes) of 196×140 km. This emitting area matches the area of the dark
24 patera floor as seen in spacecraft images (Veeder et al. 2011), but the shape is simplified from the irregular
25 annular shape of the real patera. Such a simplification is reasonable given the other uncertainties in geometry
26 and physics. While the assumed geometry affects the retrieved propagation velocity, the areal overturn rate is not
27 highly sensitive to this geometry and is constrained directly (see Section 4.2).

Figure 1: Time-evolution of lava crust properties for different thermal models: Basaltic and Modified Basaltic models use the *Standard* and *Modified* thermal properties given in Table 2, and the Ultramafic model uses the thermal properties given for this magma composition by Davies et al. (2005).

28 In the model, an overturn front propagates at a fixed velocity along the long axis of the ellipse until the entire
1 area has been resurfaced, following the Matson et al. (2006) model, which is based on the periodically-overturning
2 lava lake model introduced by Rathbun et al. (2002). The ellipse is divided into surface area segments defined
3 so that one segment is overturned every time interval Δt , and the segment areas are calculated from the ellipse
4 geometry as described in Figure B1 of Matson et al. (2006). The thermal emission timeline produced by the
5 model includes a spike as each segment founders (most prominent at short wavelengths), followed by a decay. One
6 feature of modeling the overturn as a series of foundering segments is therefore that the measured emission varies
7 greatly depending on the time interval between the last segment foundering and the data being taken. We choose
8 to always evaluate the model a fixed amount of time τ after the most recent segment has overturned. Different
9 combinations of choices for the parameters Δt and τ are tested in the model fits, including a continuous overturn
10 model which assumes that the overturn front moves continuously at a constant velocity. The spread in best-fit
11 models produced using these parameters gives a sense for the uncertainties in the model fits due to uncertainties
12 in the exact details of the overturn progression.

13 The default overturn has a propagation velocity of 1 km/day and a total cycle duration of 540 days, consistent
14 with observations of brightening cycles prior to 2001 (Matson et al. 2006; Rathbun et al., 2002; Davies 2003).
15 However, the cycle duration and overturn velocity depend sensitively on the magma properties and thus may
16 vary between brightenings (Rathbun and Spencer 2006). The default values do not provide a good fit to the
17 observations presented here, and the overturn velocity v and cycle duration N_{cyc} are left as free parameters in the
18 model fits, allowing different velocities and durations for each brightening event.

19 The temperature of each surface area unit at each time-step is calculated from the cooling model (Section 3.1).

20 The emission from the lake is then calculated using Planck's Law for blackbody radiation:

$$F_{\lambda}(t) = \sum_{i=1}^n \frac{c_1 A_i \epsilon}{\lambda^5} \frac{1}{e^{c_2/\lambda T_i(t)} - 1} \text{ [W}/\mu\text{m}] \quad (6)$$

21 and the total wavelength-integrated thermal power is

$$F(t) = \sum_{i=1}^n \sigma A_i \epsilon T_i(t)^4 \text{ [W]} \quad (7)$$

22 where $c_1 = 2hc^2/\pi = 3.7413 \times 10^8 \text{ W}/\mu\text{m}^4/\text{m}^2$ and $c_2 = hc/k_B = 1.4388 \text{ }\mu\text{m}\cdot\text{K}$. A_i is the area of the i th surface
 23 element in units of m^2 , ϵ is the emissivity, and the wavelength λ is expressed in μm . Flux densities can be expressed
 24 per steradian by dividing by a factor of π .

25 Analysis of high-resolution *Galileo* NIMS images of the southern half of Loki Patera suggested the presence of
 26 hot cracks through the crust (Davies 2003). Matson et al. (2006) did not include cracks in their thermal model,
 27 determining that the total crack fraction was too small to be significant. Cracks or other localized high-temperature
 28 activity would preferentially affect shorter wavelength data. Although the models presented here are fit only to
 29 the 3-5 μm data, the presence of such features could account for some of the emission at 2- μm wavelengths seen
 30 in the figures.

31 3.3. Thermal Properties

1 The Matson et al. (2006) model fixes the thermal properties of basalt at specific parameters based on those
 2 estimated by Davies (1996) for Ionian lavas. These authors note that the available data did not warrant a more
 3 complex model. However, the thermal properties of lavas on Earth are observed to depend strongly on properties
 4 including temperature and porosity; Patrick et al. (2004) give a concise summary of decades of analytical and
 5 experimental work on thermal properties of lava flows on Earth. The *Standard* thermal model used by Matson et
 6 al. (2006) is tested alongside a *Modified* thermal model based on the recommendations of Patrick et al. (2004) and
 7 the model of Keszthelyi and Delinger (1996). This section describes the thermal property parameterizations used
 8 in the *Modified* model, which are summarized alongside the fixed properties from the *Standard* Model (Davies,
 9 1996; Matson et al., 2006) in Table 2.

10 3.3.1. Density

11 The overturn scenario is based on the premise that the crust forms at a low enough density to be initially
 12 buoyant, but increases in density over time until it becomes gravitationally unstable and founders (Rathbun et
 13 al., 2002; Rathbun and Spencer, 2006). A basic requirement of the model is therefore that the bulk density of
 14 the crust increase over time. Although this density change is predominantly due to the evolving porosity profile
 15 in the crust (Matson et al. 2006), the temperature-dependent density of basalt is also included in the *Modified*
 16 model. This dependency is incorporated via the formula for the density of vesicular basalt given by Keszthelyi

Table 2: Basalt Thermal Properties

Property	Symbol	Standard	Modified
Latent heat of crystallization [J/kg]	C_L	4×10^5	4×10^5
Specific heat [J/kg/K]	c_p	1500	1500 for $T > 1000$ K; $1600 - \frac{10^5}{T}$ for $T < 1000$ K
Liquidus Temperature [K]	T_{liq}	1475	1475
Lava solid density [kg/m ³]	ρ_{sol}	2800	2800
Lava liquid density [kg/m ³]	ρ_{liq}	2600	2600
Crust density [kg/m ³]	ρ_{crust}	ρ_{sol}	$\frac{\rho_{sol}}{1 + \beta(T - 1450)}$
Lava thermal conductivity [W/m/K]	k_{bas}	0.9	1.1
Gas thermal conductivity [W/m/K]	k_{gas}	—	$(c_p + \frac{5R}{4m_{gas}})\mu$
Crust thermal conductivity [W/m/K]	k_{bulk}	k_{bas}	$k_{bas} \times \frac{[2(1-\phi)k_{bas} + (1+2\phi)k_{gas}]}{[(2+\phi)k_{bas} + (1-\phi)k_{gas}]}$
Emissivity	ϵ	0.9	0.9
Thermal diffusivity [m ² /s]	κ	$\frac{k}{\rho_{crust}c_p}$	$\frac{k}{\rho_{crust}c_p}$
Crust porosity	ϕ	—	$\phi = 30\% \times \frac{T}{T_{liq}} + 20\%$
Coefficient of thermal expansion [K ⁻¹]	β	—	1.5×10^{-5}

and Delinger (1996) based on data presented by Touloukian et al. (1989):

$$\rho_{bas} = \frac{\rho_{sol}}{1 + \beta(T - 1450)} \quad (8)$$

where ρ_{sol} is the density of solid basalt given in Table 2, and β is the coefficient of volumetric thermal expansion for vesicular basalt ($1.5 \times 10^{-5} \text{ K}^{-1}$; Keszthelyi and Delinger, 1996). This parameterization gives a density that increases by $\sim 50 \text{ kg/m}^3$ as the crust cools from the liquidus temperature down to 250 K. The effect on the model of including this temperature-dependence is minor; the term is included primarily for completeness in the treatment of the increase in crust density with time.

3.3.2. Porosity

The porosity of the crust affects its thermal conductivity and its bulk density, impacting its cooling rate and thermal emission as well as triggering overturn initiation when the bottom of the crust layer becomes dense enough to create a gravitational instability (Matson et al. 2006). Measurements of the Hawaiian Alae lava lake (Peck et al., 1966) revealed surface porosities of 40%, decreasing almost exponentially to around 10% at depth. This is consistent with the work of Leone and Wilson (2001), who used the dynamics of plumes on Io to infer a volatile mass fraction of $\sim 30\%$, as well as with the calculation by Matson et al. (2006) for Loki Patera considering SO_2 content and pressure. Matson et al. (2006) developed a model for the evolving porosity profile of Loki Patera as a function of crust thickness; the porosity reaches a maximum of 50% porosity at the surface decreasing with depth to a minimum of 5-10% at the base of the crust, assuming a crust thicknesses in the 5-10 meter range. Their model provides a physical mechanism for understanding why and when the crust becomes unstable and overturn is triggered. However, the porosity is not incorporated into the Matson et al. (2006) thermal model, and is therefore not included in the *Standard* model used here.

The primary outcome of including porosity in the thermal model is to decrease the bulk thermal conductivity

of the crust. Although incorporation of the time- and depth-dependent porosity into the thermal model is beyond the scope of this paper, the *Modified* model includes a simple parameterization describing the decreasing average porosity of the crust with time. The description is based on the Matson et al. (2006) model, in which the average porosity of the crust decreases from 50% for a thin crust to ~20% around the time that overturn is triggered. Due to other uncertainties in the thermal model, the model-fitting is not sensitive to the exact shape of this decrease, and a linear profile is used in the *Modified* models:

$$\phi = 30\% \times \frac{T}{T_{liq}} + 20\%, \quad (9)$$

which achieves the required value for both high and low temperatures.

3.3.3. Thermal conductivity

Typical basalts have thermal conductivities in the range of 0.9-4.0 W/m/K (Davies 2007). Peck (1978) recorded thermal conductivities of 0.1-1.8 W/m/K in the porous crust of the Hawaiian Alae lava lake, noting changes with vesicularity and temperature. By comparing model cooling curves with cooling data from the crust of a Hawaiian pahoehoe flow (Flynn and Mougini-Mark, 1992), Davies (1996) note a favorable correspondence for a value of $k = 1$ W/m/K, although the data also compare favorably with models using values of k from slightly below 1 up to nearly 3 W/m/K. The value chosen for models of Ionian basalts has often been on the low end of this range, between 0.6 and 0.9 W/m/K (Davies 1996; Matson et al., 2006; Davies 2007).

Studies of basalts on Earth disagree about whether the thermal conductivity increases with temperature (e.g. Birch and Clark, 1940; Robertson, 1988) or decreases as temperature increases (e.g. Murase and McBirney, 1973; Dunn et al., 1983). Patrick et al. (2004) discuss the evidence for each case, noting a strong consistency in the results of the latter group. The high density of observations during the cooling phases of the Loki Patera brightenings in 2013 and 2014 place constraints on the shape of the cooling curve. Models with a thermal conductivity that increases with temperature are unable to match the shape of this curve. Models with a thermal conductivity that increases as the lava cools are able to fit the observations, but give no significant improvement in fit over models with a constant thermal conductivity. The *Modified* thermal model therefore assumes a basalt thermal conductivity without temperature dependency. However, the *bulk* thermal conductivity of the crust does increase during cooling due to the temperature-dependence of the lava porosity. Values for the basalt thermal conductivity between 0.9 and 1.2 W/m/K (corresponding to bulk thermal conductivities of 0.55-0.75) are explored in the fits; values outside of this range predict too little or too much emission to match the observations, assuming a fixed overturn area of 2.15×10^4 km².

The porosity ϕ of basalt also has a significant effect on the bulk thermal conductivity k_{bulk} . The model follows Rathbun et al. (2002) and Keszthelyi and Delinger (1996) in using the porosity dependence of Maxwell (1891), which calculates the bulk thermal conductivity k_{bulk} in terms of the thermal conductivity of the lava k and of the

17 gas k_{gas} , taken here to be SO_2 :

$$k_{bulk} = k \frac{2(1-\phi)k + (1+2\phi)k_{gas}}{(2+\phi)k + (1-\phi)k_{gas}}. \quad (10)$$

18 The thermal conductivity of a gas is given by (Bird et al., 1960):

$$k_{gas} = (c_p + \frac{5}{4} \frac{R}{m_{gas}}) \mu \quad (11)$$

19 where R is the gas constant, m_{gas} is the molar mass, and μ is the dynamic viscosity, given by Sutherland's formula
20 (Sutherland 1893)

$$\mu = \lambda \frac{T^{3/2}}{T + C} \quad (12)$$

21 where λ and C are constants of the gas, which are $1.7684 \mu\text{Pa}\cdot\text{s}/\text{K}^{1/2}$ and 416 K respectively, for SO_2 gas. The
22 net result of including vesicles in the treatment of the thermal conductivity is a reduction in the bulk crust
23 conductivity of 30-40%. The thermal conductivity of the gas within the vesicles themselves contributes $<5\%$ to
24 the bulk conductivity.

25 3.3.4. Specific heat capacity

26 A formula approximating the change in the specific heat capacity of lava with temperature is presented in
27 Keszthelyi (1994) based on laboratory data in Touloukian et al. (1989). This formula assumes a maximum (high-
28 temperature) specific heat of 1100 J/kg/K . For the *Modified* thermal model, this formula is adjusted to match the
29 maximum specific heat to the value of 1500 J/kg/K used by previous authors for Io (Davies, 1996; Matson et al.,
30 2006):

$$c_p = 1500 \text{ J/kg/K for } T > 1000 \text{ K} \quad (13)$$

$$c_p = 1600 - \frac{10^5}{T} \text{ J/kg/K for } T < 1000 \text{ K} \quad (14)$$

32 3.4. Fits and Model Comparison Metrics

33 The model fits employ the Python **emcee** implementation (Foreman-Mackey et al., 2013) of an affine-invariant
34 ensemble Markov chain Monte Carlo (MCMC) method (Goodman and Weare, 2010), which has been used in the
35 past for planetary science applications (e.g. de Kleer et al., 2015).

36 Discriminating between models requires careful treatment of the degree of model complexity. Although the
37 determination of best-fit parameters for a given model relies on χ^2 minimization, χ^2 is not a meaningful metric
38 for comparison between non-linear models because the number of degrees of freedom is not in general well-defined
39 (Andrae et al. 2010). Although χ^2 values for model fits are given in the results section, these are intended to give
40 a rough sense of the fit quality and should not be used for quantitative comparison between models.

41 Instead, two model-comparison metrics are employed to distinguish between models: the Deviance Information
42 Criterion (*DIC*) and the Kolmogorov-Smirnov Test (KS-test) p -value. The *DIC* combines a standard term
1 for goodness-of-fit with a penalty term for model complexity, and considers the full posterior distribution of

each parameter, allowing comparison of the models themselves rather than their single best-fit manifestations (Spiegelhalter et al. 2002). Smaller values correspond to better fits; values are reported in the form of ΔDIC , the difference between the value for a given model compared with that of the best model (lowest DIC value). This metric is explained in more detail in de Kleer et al. (2015), and is particularly convenient because it is simple to calculate from the output of MCMC simulations.

The KS-test (Kolmogorov 1933; Smirnov 1948) is reported because it gives insight into whether the deviations from the model are random or systematic; systematic deviations indicate an incorrect model, even if the χ^2 value is small. The KS-test checks the likelihood that a given dataset (in this case, the residuals from the model fits) is consistent with a given distribution (here, the Gaussian distribution). Residuals consistent with a Gaussian distribution indicate a correct model; an incorrect model can be identified by a skewed distribution, by too much power in the wings, or by a very peaked noise distribution indicative of a model that overfits the data. If the p -value is less than one minus the chosen significance level, the hypothesis that the residuals are drawn from a Gaussian distribution can be rejected.

4. Analysis and Results

The original magma sea model (Matson et al. 2006) provides a good fit to the first two overturns, provided the following three parameters are allowed to vary: the propagation velocity of overturn front, the interval between the start of successive overturns, and the background intensity level. Fits using this model are shown in Figure 2. The background intensity parameter is an additive scalar value that is fixed over time per brightening event, representing activity in the patera that is independent of the overturn, such as the active southwest margin observed by *Galileo* (Spencer et al. 2000; Davies 2003; Howell & Lopes 2007). Although the best-fit values for this parameter are low relative to Loki Patera’s total emission (<5 GW/ $\mu\text{m}/\text{sr}$), the parameter is required to fit the data during the quiescent phase without invoking high thermal conductivities that fit the data poorly at earlier times. The third overturn is not well fit by the standard overturn model; in particular, the short duration of the bright period cannot be matched by the model without drastically over-predicting the thermal emission. A forward model with an overturn velocity of 2 km/day (at the upper end of the velocities determined in the past for Loki Patera) is shown in Figure 2. Although the K-band ($2.3\text{-}\mu\text{m}$) data and models are shown in the figures, in all cases the model-fitting is based on only the L- and M-band (3.8- and $4.7\text{-}\mu\text{m}$) data. The short wavelength data are omitted from the fits because they are very sensitive to features such as localized irregularities in the overturn propagation or the presence of cracks in the crust (Davies 2007), which are not included in the model.

A rise in intensity during the nominal cooling phase suggests that the third brightening was more complex than a single, fixed-velocity overturn. The data lack the time-resolution to determine the specific details of the overturn progression, and two simple alternatives are therefore modeled: a two-phase overturn, and an overturn that resurfaces only a fraction of the patera. Allowing a two-phase resurfacing event improves the model fit somewhat, but still predicts higher intensities than seen in the data (see Figure 2). If the percentage of the patera

Table 3: Best-fit Model Parameters: First Two Brightenings

Model ^a				Parameters				Fit Quality ^b					
<i>Thermal Model</i>	<i>Geo</i>	ΔT [days]	τ [days]	v_0 [km/day]	v_1 [km/day]	$\bar{A}_0$ [m ² /s]	$\bar{A}_1$ [m ² /s]	χ_1^2	χ_2^2	p_1	p_2	ΔDIC_1	ΔDIC_2
Std	Ellip	1.0	0.5	1.25±0.14	1.31±0.13	1600	1660	12.3	21.8	0.87	0.14	1.3	1.0
Std	Ellip	1.0	1.0	1.42±0.16	1.52±0.18	1800	1910	14.6	22.1	0.95	0.27	2.8	0.0
Std	Ellip	0.1	0.05	1.19±0.13	1.22±0.12	1520	1560	11.2	23.1	0.61	0.05	0.0	2.2
Std	Ellip	0.1	0.1	1.22±0.14	1.26±0.13	1560	1600	11.8	22.4	0.59	0.04	0.9	1.6
Std	Ellip	<i>Continuous</i>		1.19±0.13	1.20±0.13	1520	1540	10.7	25.0	0.40	0.02	0.1	1.9
Std	Rect	1.0	0.5	1.33±0.14	1.50±0.16	1680	1910	10.5	22.2	0.61	0.08	0.5	0.0
Mod	Ellip	1.0	0.5	1.65±0.19	2.16±0.40	2110	2760	13.3	37.8	0.84	<0.01	2.9	13.8

^a All models have a fixed total patera surface area of 2.15×10^4 km².

^b See Section 3.4 for interpretation of the metrics. In general, better models have lower χ^2 and ΔDIC values, while p -values below 0.02 rule out models at the 98% level. Note that χ^2 is not a meaningful metric for comparison between models. In addition, χ^2 and ΔDIC values cannot be use to compare directly between different overturn events.

Table 4: Best-fit Model Parameters: Third Brightening

Model				Parameters				Fit Quality ^a		
<i>Thermal</i>	k_{bas}	k_{bulk}	N_{phase}	$frac$	$frac_{cover}$	v	$\bar{A}$	χ^2	p	ΔDIC
Std	0.9	0.9	2	0.58±0.05	0.63±0.05	1.11±0.17	1410	18.9	0.53	0.0
Mod	0.9	0.57	2	0.59±0.05	1	1.70±0.21	2150	20.3	<0.01	3.8
Mod	1.0	0.63	2	0.57±0.04	1	1.69±0.18	2150	20.1	0.04	1.6
Mod	1.1	0.69	2	0.56±0.04	1	1.74±0.18	2220	23.0	0.19	1.2
Mod	1.2	0.75	2	0.56±0.04	1	1.88±0.23	2390	28.7	0.35	7.5

^aSee Section 3.4 for interpretation of the metrics. In general, better models have lower χ^2 and ΔDIC values, while p -values below 0.02 rule out models at the 98% level. Note that χ^2 is not a meaningful metric for comparison between models. In addition, χ^2 and ΔDIC values cannot be use to compare directly between different overturn events.

overtaken during the brightening is left as a free parameter, model fits find that only ~60% of the patera is resurfaced. This model is compared with models for which the entire patera overturns in Figure 3 and Table 4, and provides a comparably good fit to the model with *Modified* thermal properties in which the entire patera is resurfaced.

An alternate resolution to the poor model fit to the third brightening is that the thermal properties may be incorrect. The thermal properties used for past modeling of Io’s lava flows (Matson et al. 2006; Davies 2007) were adopted as typical values for basaltic composition, but were not well-constrained by past data. The following sections discuss the results of varying the thermal parameters as described in Section 3.3 and of varying the patera geometry and the continuity of overturn. Models assuming a single overturn fail to fit the data regardless of input parameters, and all fits therefore assume a two-phase overturn, which is adopted as the simplest parameterization of a complex overturn progression.

4.1. Thermal Properties

The modifications made to the original magma sea model (Matson et al. 2006) include the porosity, specific heat capacity, density, and thermal conductivity (see Section 3.3). Of these properties, the porosity ϕ and the thermal conductivity k of the lava have the greatest impact on the quality of fit (though the porosity impacts the model

Figure 2: Timelines of the three brightening events with the original Matson et al. (2006) overturning magma sea model. For the first two events, the model is fit to the data with the velocity of overturn, interval between successive overturns, and background intensity level as free parameters in the fits. For the third overturn, the model does not provide a good fit to the data, and models are shown demonstrating the resurfacing of the patera in both one and two phases with an overturn velocity of 2 km/day (not fit to the data). Circles are observations with $\mu > 0.7$ and were used in the fit; points are limb-viewing observations with $\mu < 0.7$ which were not used in the fits. Note the difference in y-axis scale between the two panels.

primarily through its effect on the bulk thermal conductivity). In general, models with lower thermal conductivities predict shorter bright phases given the observations, since higher overturn front velocities are required to match the peak intensities observed. The durations of the first two overturns are unconstrained by the observations, and models with a range of thermal properties fit the data well. In contrast, the duration of the third brightening event is well-constrained, and this event is used to constrain the thermal properties within the framework of the model assumptions.

Figure 4 shows best-fit models to the third event for basalt thermal conductivities from $k = 0.9 - 1.2$ W/m/K and other thermal properties fixed at the *Modified* model values. These models all predict more realistic peak intensities than the *Standard* thermal model; the best fits are achieved for $k = 1.0$ and 1.1 W/m/K. However, the $k = 1.0$ W/m/K case does not find a good fit to the first two brightenings, and the residuals from the third brightening are suggestive of systematic deviations; $k = 1.1$ W/m/K is therefore chosen as the nominal model value. All choices for k find similar values for the fraction of the lake that is overturned for the first versus second phase of the third event, but the overturn velocity is higher for larger values of k . Note that because the *Modified* model incorporates porosity into the calculation of bulk thermal conductivity, a basalt thermal conductivity of 1.1 W/m/K corresponds to a *bulk* thermal conductivity of 0.7 W/m/K (see Table 4), which is lower than that used by the *Standard* model.

Models with the *Modified* thermal properties, including a bulk thermal conductivity of $k = 1.1$ W/m/K, also provide a reasonable fit to the 2013 brightening event, but are ruled out by both the KS-test and the *DIC* for the 2014 event. However, there are no data from the first part of the 2014 event; this discrepancy could be improved by postulating a more complex or multi-phase overturn, but the lack of data preclude including these complexities

Figure 3: Model for the third brightening event using *Standard* thermal properties and a best-fit resurfacing fraction of 0.63, compared with models in which the entire patera is resurfaced. The *Standard* model is a forward model with a velocity of 2 km/day, while the other two models are fit to the data. The magenta, blue, and cyan points correspond to M-, L-, and K-band data, as in the other figures, and the rightmost panel is a close-up view of the boxed region indicated on the main panel.

in the model. It should be noted that the third brightening is the only event which was observed from beginning to end and whose duration is constrained, and for which the models therefore have the least ambiguity. However, assuming a single-phase overturn, the best fit for the 2013 and 2014 events is still obtained for the *Standard* thermal properties (see Figure 5).

4.2. Geometry

The geometry of the patera as seen in spacecraft images is complex; moreover, the propagation of the overturn front is likely not a smooth, linear process. For a fixed overturn front velocity, the patera geometry determines the area overturned each day, and thus the shape of the thermal timeline. To test the magnitude of influence the adopted geometry has on the model fits, models with both elliptical and rectangular geometries are considered.

The results of these fits are shown in Figure 6 and the parameters are given in Table 3. The dominant effect of changing the model patera geometry is on the specific shape of the thermal timeline during the peak activity; models for different patera geometries converge rapidly after the active overturn phase has ended. While the elliptical geometry provides a slightly better fit, the values of the quality-of-fit metric for the two geometries are close enough that this improvement is not statistically significant. In addition, the retrieved velocities for both overturns are consistent within uncertainties. The differences between the elliptical and rectangular models are therefore not significant, and can be considered representative of the uncertainties introduced into the fits by using a simplified shape model.

Figure 4: Fits to the thermal emission during the third brightening event for models with different thermal properties, assuming a two-phase overturn. All “Mod” models use the *Modified* thermal properties, with the basalt thermal conductivity k_{bas} given in the legend in units of W/m/K. The *Standard* model is a forward model with a velocity of 2 km/day, while the other models are fit to the data. The magenta, blue, and cyan points correspond to M-, L-, and K-band data, as in the other figures, and the rightmost panel is a close-up view of the boxed region indicated on the main panel.

4.3. Continuity of Propagation

The foundering and sinking of portions of a lava lake crust is a non-uniform process on Earth (e.g. Wright et al., 1968). The temperature distribution on the floor of the patera determined from *Galileo* observations revealed this to be the case for Loki Patera as well (Davies, 2003; Howell and Lopes 2007). The thermal emission at the time of a given observation is extremely sensitive to the amount of young magma exposed at that moment, and therefore to the size of the most recent foundering portion and how long ago it sank. If only 1% of the lake has foundered within the past half day, the $3.8\text{-}\mu\text{m}$ emission will be $>50\text{ GW}/\mu\text{m}/\text{sr}$, nearly a third of the peak intensity. Figure 7 demonstrates that the entire area of Loki Patera at 300 K has a comparable $3.8\text{-}\mu\text{m}$ intensity to a small area of 100 km^2 one day after overturn (i.e. $\sim 0.5\%$ of the lake area at 540 K), and as an area of 10 km^2 0.1 days after overturn (i.e. $\sim 0.05\%$ of the lake area at 690 K). Additionally, as can be seen in Figure 7, these three scenarios have drastically different ratios of intensity between the observed wavelengths, illustrating the impact of the overturn continuity on the thermal model, and the importance of observations at multiple wavelengths.

The continuity of overturn is parameterized by the two parameters Δt and τ (introduced in Section 3.2), which give the time interval between the foundering of successive portions of the crust, and the time between the last raft sinking and a given observation being made. Models using different values for these two parameters are fit to the first two overturns, as is a model for continuous overturn which assumes that the propagation wave moves continuously instead of the foundering occurring in large rafts.

Figure 8 demonstrates the best-fit models for cases with $\Delta t = \{0.1, 1.0\}$ days and $\tau = \{0.5, 1.0\} \times \Delta t$, as well as a continuous overturn model; the best-fit parameters for these fits are given in Table 3. All models find a comparably

Figure 5: Fits to the first two brightening events using models with *Standard* and *Modified* thermal properties. The *Standard* model is as shown in Figure 2. The parameter values for the models are given in Table 3. The magenta, blue, and cyan points correspond to M-, L-, and K-band data respectively, and the left panel is an enlargement of the indicated region in the right panel.

24 good fit to the data, although models predicting greater short-wavelength emission produce residual distributions
 25 for the 2014 event that are somewhat non-Gaussian. The overturn velocities for both events are consistent within
 26 uncertainties in all cases. Because the size of the rafts and interval between foundering area likely non-uniform,
 27 the range of models plotted in Figure 8 can be interpreted as giving a qualitative sense for the degree of variability
 28 expected due to this non-uniformity.

Figure 6: Model fits to the 2013 and 2014 overturn events for *Standard* thermal properties and two different patera geometries. Both geometries provide comparable fits to the data. The magenta, blue, and cyan points correspond to M-, L-, and K-band data respectively, and the left panel is an enlargement of the indicated region in the right panel.

Figure 7: The 2-5 μm thermal emission spectra for three areas at different temperatures, comparing the entire lake at a typical quiescent temperature of 300 K with the total emission from small areas of 10 and 100 km^2 at high temperatures corresponding to 0.1 and 1.0 days post-overturn, respectively. A comparison of the three curves demonstrates that a small hot area can produce comparable K- and L-band emission to the entire patera during quiescent times.

Figure 8: Model fits to the 2013 and 2014 brightenings for different values of Δt and τ , the time interval between successive rafts sinking and the time between the last raft sinking and the current observation. A continuous model is also shown, in which the propagation wave moves continuously at a constant velocity. The differences between the models are mainly due to the amount of high-temperature lava exposed at any given time. The magenta, blue, and cyan points correspond to M-, L-, and K-band data respectively, and the left panel is an enlargement of the indicated region in the right panel.

5. Discussion

5.1. Overturn model

5.1.1. 2013 and 2014 brightenings

For the brightening events in 2013 and 2014, the Matson et al. (2006) model provides a good fit to the thermal emission timelines at wavelengths of 2.3, 3.8, and 4.7 μm , with a few caveats. The velocity of overturn front propagation, and the time between successive brightenings, must be left as free parameters. While the nominal model includes an overturn front velocity of 1 km/s and an average cycle duration of 540 days, the best-fit models for these brightenings find velocities around 1.3 km/s and cycle durations of 440 and 540 days respectively, with uncertainties of 20 days. In addition, the observed intensity during the quiescent phase is higher than that predicted by the model, and a parameter for the background level of thermal activity beyond the overturn must be included to obtain a close fit at these times. This background emission may represent localized activity such as active margins, or may be due to changes in the lava properties during cooling that are not accurately described by the model.

It is important to note that no data were obtained during the early phases of the events, and the durations of the events are consequently nearly unconstrained. While models with different thermal properties and overturn continuities achieve comparable fit qualities in many cases, they predict very different bright-phase durations. If data from the early part of the events existed, they would provide a clear constraint for distinguishing between these models.

5.1.2. 2016 brightening

In contrast to the first two events, the duration of the third brightening is closely constrained, and the original Matson et al. (2006) model is not able to fit the data. Postulating that the overturn proceeds in two phases, as suggested by a sharp rise in emission during the cooling phase and consistent with past observations (e.g. Rathbun and Spencer 2006), mitigates the problem somewhat. However, obtaining a good fit to these data requires a mechanism that reduces the emission from the patera during the overturn. Two mechanisms are explored that could produce such an effect: the thermal properties of the lava, and the fraction of the patera that is resurfaced.

Both of these mechanisms introduce potential discrepancies with either past observations or other aspects of the model. If the thermal properties are modified so that the entire patera can be resurfaced during the third event without producing implausibly high emission, the first two events must also be shorter than predicted by the *Standard* model. While the original model produces bright-phase durations of 170-200 days, consistent with the typical ~ 7 -month bright phase observed in the past (Rathbun and Spencer 2006), the modified durations are closer to 100-120 days. In the overturn model, the peak brightness scales inversely with the duration of the event; these events are not significantly brighter than past events, so such short durations contradict this correlation. In addition, the thermal properties that provide the best fit to the 2016 brightening do not provide a good fit to the 2014 brightening, and predict an overturn front propagation velocity twice that of the other models.

These discrepancies may be mitigated by assuming more complex, multi-phase overturns, but such models are not warranted by the data, which lack coverage during the early phase of the 2013 and 2014 brightenings.

An alternative solution, which supposes that only a fraction of the patera is resurfaced during the third event, resolves these discrepancies but requires a mechanism that halts the overturn when only a fraction of the patera has been resurfaced. Neither mechanism is therefore completely satisfactory, although both provide a good fit to the data. The future application of these models to brightening events prior to 2013 may discriminate between possibilities.

5.1.3. Constraints from past brightenings

Under the assumption that the entire patera is resurfaced each cycle, there is a clear anti-correlation between bright-phase duration and peak brightness (faster overturns result in larger areas of high-temperature lava at a given point in time). This correlation can be used for a coarse assessment of the predictions of the different models in the context of previously-observed brightening events.

Prior to 2001, typical peak 3.5- μm brightnesses were in the 80-100 $\text{GW}/\mu\text{m}/\text{sr}$ range with three events surpassing 100 $\text{GW}/\mu\text{m}/\text{sr}$ (Rathbun et al., 2002), and the average bright phase duration was 230 days. The peak 3.8- μm brightness observed in the 2013 and 2014 brightenings was around 130 $\text{GW}/\mu\text{m}/\text{sr}$, while the bright-phase durations were just under 200 days for the *Standard* model and 100-150 days for the *Modified* model. These events are thus somewhat shorter than pre-2001 events, despite having the same peak brightness (note that the intensity at 3.8 μm is $\sim 40\%$ higher than the intensity at 3.5 μm for a 300 K surface). The peak 3.8- μm brightness for the 2016 event was 150 $\text{GW}/\mu\text{m}/\text{sr}$ for an event lasting only ~ 100 days, which breaks the expected correlation unless intensities much higher than those detected were present on days when no data were obtained.

The areal production rates of 1500-1800 m^2/s for the 2013 and 2014 brightenings is somewhat higher than the rates estimated for previous brightenings ($\sim 1000 \text{ m}^2/\text{s}$; Howell et al., 2001; Rathbun and Spencer, 2006). However, the past estimates assumed that the resurfacing was active for nearly the entire duration of the bright phase, while the model used in this analysis predicts that active resurfacing ceases shortly after the peak brightness is attained, which can account for a factor of ~ 2 difference.

5.1.4. Total Thermal Emission

Previous authors have estimated that Loki Patera produces 10-15% of Io's total heat flow (Spencer et al., 2000; Matson et al. 2006; Veeder et al. 2011), and the Matson et al. (2006) model yielded a minimum power of 5.7 TW and a maximum of 15.6 TW, excluding cracks and active margins. Models with velocities and cycle durations typical of the 2013 and 2014 brightenings predict a total time-averaged heat flow around 8 TW ($\sim 10\%$ of Io's total heat flow), reaching over twice that at the peak of the brightening phase.

This estimate for Loki Patera's heat flow is dependent on model parameters, and in particular requires emission from an area of 21,500 km^2 , the surface area of the low-albedo feature in spacecraft images (Veeder et al. 2011). For dates when observations are made at multiple near-infrared wavelengths, an independent estimate of the total

thermal emission can be made by fitting a simple model for Loki Patera as a large area of uniform temperature, leaving both temperature and area as free parameters. The thermal emission calculated in this way is typically about half that predicted by the model. The reason for this is illustrated in Figure 9, where it can be seen that the bulk of the emission is coming from wavelengths longer than $5\ \mu\text{m}$; the single-temperature (1T) fit to the 2-5 μm data misses a significant portion of emission from large cool areas that is captured by the more physically-motivated overturn model. On the date shown, data out to $12\ \mu\text{m}$ were obtained (de Pater et al. 2017), and it is clear that the overturn model captures this longer-wavelength emission well.

Figure 9: Comparison of model spectra for observations on Sep 24, 1999, ~ 24 days after the start of a brightening event, on which data from 1-12 μm were obtained (de Pater et al., 2017). The overturn model is calculated for a resurfacing velocity of 1.0 km/day and the 24th day of overturn. The figure illustrates that the total heat flow predicted by the overturn model exceeds that of a single-temperature (1T) fit to the 2-5 μm data by a significant amount due to the inclusion of a large low-temperature region in the overturn model whose dominant emission is at longer wavelengths than are probed by near-IR observations. The filters K, L, and M are centered at 2.3, 3.8, and 4.7 μm respectively.

As can be seen from Figure 9, simultaneous observations in the near-infrared and at longer infrared wavelengths (8-12 μm) provide a valuable validation of the overturn model.

5.1.5. Geometry and continuity of overturn

The thermal emission timelines are set by the surface area that is resurfaced each day, which is a function of both the overturn velocity and the patera geometry. Test fits using a rectangular geometry and elliptical geometries with different axis ratios indicate that the model is not particularly sensitive to the adopted geometry. The main difference in the thermal emission timelines produced by these models is the abruptness with which the brightening phase begins and ends, but the degree of difference is generally within the uncertainties of the observations.

Models with different sizes of foundering rafts and intervals between successive rafts sinking also find similar overturn velocities and fit qualities, including the continuous-overturn model, and give a sense for the degree of day-to-day variability that might be present during the overturn event.

5.2. Active regions and direction of resurfacing

A comparison of *Voyager 1* and *Voyager 2* images of Loki Patera indicated movement of a high-temperature front from the southwest corner of the patera toward the east, moving at approximately 1 km/day (Pearl and

Figure 10: The location of the source of peak thermal emission from Loki Patera as a function of cycle phase, given in % of the total number of days in an overturn cycle (~ 450 days). The gray region is the low-albedo patera area as seen by *Voyager* (Veeder et al. 2011). When locations were determined at multiple wavelengths, the mean location is shown. Triangles indicate observations during the nominal overturn phase according to the model, while circles indicate observations taken during the cooling phase. Note that the emission is not resolved in these observations, and positions represent an average or centroid of the emission sources within the patera. Stars give the approximate locations derived by LBT observations that do resolve emission within the patera (Conrad et al., 2015).

Sinton, 1982; Rathbun et al., 2002). High-resolution *Galileo* images of the southern half of Loki Patera using the PPR instruments in 1999 and 2000 and the SSI instrument in 2001 agreed with this direction and rate of motion (Spencer et al., 2000; Davies, 2003; Howell and Lopes, 2007).

Although the location of the emission within the patera is poorly constrained by ground-based observations, the best-fit locations of emission as a function of overturn phase suggest overall movement of emission in a clockwise direction (see Figure 10), consistent with observations made during the peak of the brightening event seen in 2009 (de Pater et al., 2017). However, the initial phase of brightening is typically rapid, and no observations were made during this phase of the 2013 and 2014 brightenings. In the 2016 brightening, the northern origin of the emission early in the brightening phase supports clockwise motion, as do observations from recent years. In 2010, de Pater et al. (2014b) observed Loki Patera five times within a two-month period, detecting an increase in intensity from 30 up to nearly 100 $\text{GW}/\mu\text{m}/\text{sr}$ at $3.8 \mu\text{m}$. During this brightening, the source of the emission was centered around 306.5°W 16°N , in the northeast corner of the patera. Both the location and magnitude of emission from the 2010 data are consistent with the model assuming propagation beginning in the north of the patera and propagating in a clockwise direction.

According to the foundering model, resurfacing begins wherever the first portion of crust founders. Although this is most likely the area where the crust is oldest and therefore least stable (Rathbun et al., 2002), localized activity in or near the patera could trigger a different portion to overturn first, reversing the direction of propagation. The observations also suggest that the source of peak emission may move back and forth across the southern portion of the patera within the overall east-to-west trend, or perhaps that the southwest and southeast corners are active outside of the regular overturn. The indications of counter-clockwise movement from spacecraft observations were based on emission only within the southern half of the patera; it is possible that the apparent directionality represented local instead of global propagation, and that the resurfacing has always occurred in a broadly clockwise direction. Based on $2.2\text{-}\mu\text{m}$ ground-based speckle imaging, Macintosh et al. (2003) detected an eastward shift in emission of 100 km over the course of a month, toward the end of a brightening phase. The east-west motion and measured fluxes in the $4\text{-}8 \text{ GW}/\mu\text{m}/\text{sr}$ range is very similar to what was observed in 2013-2016

for this portion of the overturn, despite the overall movement in the opposite direction.

There are also indications from other ground-based data that activity at Loki Patera is not as simple as a single overturn front propagating around the patera. Two separate high-temperature emitting regions separated by 100 km were observed during the 1991 Loki Patera brightening (Goguen et al., 1993). Rathbun and Spencer (2006) required a model with a varying propagation velocity within each overturn to match observations of early brightening events. The presence of multiple hot regions with different velocity and timing could produce a similar thermal signature.

In addition, the cumulative evidence from the 2013-2016 brightenings at Loki Patera, as well as past observations, point to sections of the patera that remain active outside of the nominal overturn. In the model fits presented here, a background-intensity parameter is required to fit the observations during the quiescent periods. In the absence of such a parameter, the model predicts much lower intensities during these times than are observed. This effect is also evident in the 1997-2000 brightenings of Loki Patera (Rathbun and Spencer, 2006). While this discrepancy can also be resolved by modifying the thermal properties of the lava to radiate more at low temperatures, such modifications deteriorate the fit during other phases of the brightening cycle.

The recent LBT detection of emission from two distinct regions within the patera during the nominal cooling phase (Conrad et al. 2015) supports the existence of continuously-active zones in the southwest and southeast corners of the patera. The emission measured by the LBT is also slightly in excess of the model prediction for that date, consistent with short-lived localized activity. An active margin in the southwest is also evident in the *Galileo* high-resolution observations of Loki Patera (Davies 2003). In addition, the bulk of detections in 2013-2016 outside of the nominal overturn phase originate in one of these two margins (see Figure 10).

The repeated detection of emission from multiple locations within the southern part of the patera when models predict the crust should be passively cooling suggest that certain areas (e.g. the southeast and southwest corners) may be continually or sporadically active at all times. As the spatial resolution of observations improves, future models of Loki Patera will need to include these additional complexities.

5.3. Topography

The flux densities derived from observations when Loki Patera is viewed near the limb of Io are anomalously low compared to other temporally-close observations, indicating that the geometric foreshortening correction is not accurately recovering the flux density at high emission angle. Such an effect could be produced by mechanisms such as nearby topography, cracks through the crust which are blocked at high angles, or non-isotropic emission.

A topographic feature would take the form of either a mountain or raised region next to Loki Patera, or the edge of the patera itself if the magma level is significantly lower than this edge. The fact that the shape of the low-albedo patera region was unchanged between the *Voyager* and *Galileo* encounters in 1979 and 1997 also suggests a topographic confinement (McEwen et al., 1998), and the lack of lava spreading to the west of the patera in spacecraft images indicates a potential barrier in that direction (Spencer et al., 2000). While Loki Patera does not have an Earth analog of a similar size, it shares some characteristics with lava lakes, which on Earth are generally

2 confined in a topographic region such as a caldera, although they may overflow into the surrounding area.

3 Figure 11 demonstrates the fraction by which Loki Patera’s intensity is reduced due to viewing geometry.
 4 In the figure, the fractional dimming is plotted in the form $(I_{model} - I_{data})/I_{model}$, the intensity residuals from
 5 models with *Standard* thermal properties, $\{\Delta t, \tau\}=\{1.0, 0.5\}$, and a two-phase incomplete overturn for the third
 6 brightening. Despite the large uncertainties seen in the figure, the difference in the intensity residuals between
 7 high- and low-emission-angle observations is significant. The uncertainty-weighted mean of the obscured fraction
 8 of the patera is -0.02 ± 0.02 for low- θ points, while for high- θ points it is 0.32 ± 0.02 . This figure also shows the
 9 same parameter as a function of the difference in longitude between Loki Patera and the sub-observer point during
 10 each observation, demonstrating that the effect is present when the patera is viewed from both the east and the
 11 west, although views of the patera from the west are rare (such observations require a central meridian longitude
 12 in the narrow range between $\sim 355^\circ\text{W}$ and $\sim 40^\circ\text{W}$, which occurs primarily when Io is behind Jupiter). Over
 13 a time interval much shorter than the period of precession of Io’s periaipse (~ 1.5 years), the same sub-observer
 14 longitude is seen from Earth at the same orbital phase. However, the third panel in Figure 11 demonstrates that
 15 the fractional dimming of Loki Patera is correlated much more strongly with viewing geometry than with orbital
 16 phase (as calculated from the time since periaipse). The intensities have already been corrected for geometric
 17 foreshortening. In the case of high-emission-angle viewing geometries, there are large uncertainties in the best-fit
 18 position of the hot spot and hence the emission angle. In these cases, the intensities are corrected to the mean of
 19 the intensity using the best-fit location from the data, and the intensity given a position of $12^\circ\text{N } 310^\circ\text{W}$. All data
 20 are consistent with both intensities within the uncertainties shown.

Figure 11: The effect of viewing geometry on the measured intensity of Loki Patera. The fractional dimming of Loki Patera is given based on the model residuals $(I_{model} - I_{data})/I_{model}$, as a function of (left) μ , the cosine of the emission angle; (center) the difference in longitude between Loki Patera and the sub-observer point; and (right) Io’s orbital phase at the time of observation. Model intensities are for a model with *Standard* thermal properties and a two-phase, incomplete third overturn. Data are shown for two wavelengths and all three brightening events. As is seen in these figures, the dimming of Loki Patera is more closely correlated with emission angle than with orbital phase, and appears symmetric between eastward and westward viewing angles. Intensities have been corrected for geometric foreshortening.

21 The fractional dimming of three other persistently-active hot spots from the same dataset (de Kleer and de
 22 Pater, 2016) is shown for comparison in Figure 12. All three hot spots were stable in intensity between 2013 and
 23 2016, with one exception: Marduk Fluctus was unusually bright in 2016, and the 2016 intensity of Marduk Fluctus
 24 is therefore omitted from the figure. The model intensity for each hot spot is defined as the median intensity of
 25 that hot spot over the observation period. Marduk Fluctus and Uta Patera show no clear trend with emission

angle, while Janus Patera appears brighter when viewed from the west and dimmer when viewed from the east. All three cases differ from Loki Patera, where the dimming effect is purely a function of emission angle and is insensitive to which side the patera is viewed from.

Figure 12: The effect of viewing geometry on the measured intensity of Janus Patera, Marduk Fluctus, and Uta Patera. The fractional dimming of all three hot spots is shown as a function of μ , the cosine of the emission angle, and of the longitude difference between the hot spot and the central meridian longitude (CML) of Io. The residuals are calculated as $(I_{model} - I_{data})/I_{model}$, where the model intensity is defined as the median intensity of each hot spot. These three hot spots were chosen because of their relatively stable intensities over the period of observation, 2013-2016 (de Kleer and de Pater, 2016). The correction for geometric foreshortening appears to recover the intrinsic intensity correctly in some cases (Marduk Fluctus, Uta Patera), with definite trends in others (Janus Patera).

The fractional dimming of Loki Patera is compared to topographic models in Figure 13. The top panel considers a uniformly-emitting patera of elliptical geometry, and assumes that the dimming effect is due entirely to the magma level residing a height H below the edge of the patera. In order for such a model to match the data, the level of the magma must fall short of the edge of the patera by $H=10-20$ km. The model assumes an elliptical lake geometry without accounting for the island; however, including the island in the calculation reduces the required height by at most a factor of two. In contrast, analysis of *Galileo* images found a maximum value of 100 m for the height of the patera edge above the magma level (Turtle et al. 2004). Although the depth of lava lakes on Earth do change drastically (Tilling, 1987), a change from 100 m to 10 km would require the displacement of over 200,000 km³ of magma, an incredible amount especially considering that the overall activity at Loki Patera has shown no major changes during this time.

An alternate model is shown in the bottom panel of Figure 13. In this case, the edge height is fixed at 100 m above the magma level, but 80% of the emission arises from a margin of variable width around the edge of the patera, with the remaining 20% of the emission uniformly emitted from the entire patera. These models can achieve a reasonable match to the data for margin widths of only 200-400 m, while fitting the shape of the data more closely. As the emission angle increases, the observed dimming increases for emission angles above $\sim 50^\circ$, but reaches a maximum patera obscuration of $\sim 50\%$. A uniformly-emitting patera would produce a different

effect, whereby the dimming would increase with emission angle until the entire patera was obscured. However, if significant emission arises from a narrow active margin around the edge of the patera, this margin becomes rapidly obscured leading to an apparent step and then leveling-out of the dimming, similar to what is seen in the data. *Galileo* NIMS observations of Loki Patera at high spatial resolution indicated the highest temperatures along the inner and outer rims of the patera (Howell & Lopes 2007), although the bulk of the 4.8- μ m emission was not localized to the edges (Davies, 2003). The lack of berg features in the patera margins may also be evidence that these areas are hotter (Howell et al., 2014). Evidence for the existence of an active margin in localized areas is also discussed in Section 5.2.

The model fits find that the amount of background emission produced by a mechanism outside of the overturn itself constitutes only a third of the total emission in quiescent times, and a few percent of the total emission during peak activity. If significant emission is coming from the outer edge of the patera, this must therefore also include emission associated with the overturn itself.

Mechanisms other than topography could also produce a similar effect. Marchis et al. (2001) explored absorption in an overlying SO₂ plume to explain variations in Pele’s intensity with emission angle. An effect like this could also be produced if the majority of emission were coming from cracks through the cooler surface lava. To reproduce the shape of the data in Figure 13, such cracks would need to be ~ 3 times as wide as they are deep. A mechanism would be required to continuously generate cracks throughout the overturn cycle, since the hotter areas exposed in the cracks would cool much more rapidly than the cooler lava crust.

Figure 13: The intensity residuals of Loki Patera as a function of emission angle, calculated as $(I_{model} - I_{data})/I_{model}$ from a model with *Standard* thermal properties. (Top) Models of the fractional area of an elliptical patera obstructed by an edge of a given height; (Bottom) models of the fractional area of an elliptical patera obstructed by an edge height of 100 m and an active margin of the specified width that contributes 80% of the total intensity from the patera. Solid and open circles indicate 3.8- and 4.7- μ m data respectively. Gray points are past observations: (1) triangle - 1997 *Galileo* observation (Davies et al., 2012); (2) pentagons - 2002 Keck observations (de Pater et al., 2017); (3) diamonds - 2009 Keck observations (de Pater et al., 2017). The dotted vertical line indicates the location of 45.6° ($\mu = 0.7$); only points at lower emission angles are used in the model fits shown in this paper.

If the magma level within the patera is changing over time, it may not be meaningful to compare observations

on different days. In addition, the analysis discussed here relies on the models to calculate the intrinsic emission on a given night to compare to the observed emission, and is therefore sensitive to model inaccuracies as well as day-to-day fluctuations in thermal emission during the overturn. Both shortcomings could be circumvented by measuring the intensity of Loki Patera at all emission angles on a single night as the site rotates from limb to disk center. The obscured area could then be calculated in comparison to the intensity at disk center and would not rely on a model, nor would the interpretation be confused by day-to-day variations in thermal emission or magma level. Past programs at Keck (de Pater et al. 2017) and the CFHT and ESO (Marchis et al. 2001) have included observations along these lines, but the interpretation was hindered by poor photometric conditions in the former case, and a lack of complete emission angle coverage within a given night in the latter case.

If the depth of the magma within the patera could be measured in this way on different dates, it could be determined whether the depth is varying in time. Such variability would indicate an active connection between the lake and magma supply, which would provide insight into the mechanisms powering Loki Patera.

Galileo also measured anomalously low intensities at Loki Patera when viewed at high emission angles. Davies et al. (2012) speculated the presence of a topographic barrier based on high-emission-angle observations on June 26, 1997 (orbit C9) compared with observations at low emission angle two days later. These datapoints are shown for comparison in Figure 13 along with measurements based on Keck data in 2002 and 2009 (de Pater et al., 2017). This comparison finds no changes in the degree of dimming from 1997 through 2016, indicating that if the topography and magma level are the source of this effect, these properties are broadly stable on decadal timescales.

Not all past observations align with these findings. An analysis of observations from the 3.6-meter Canadian-France-Hawaii Telescope (CFHT) and European Southern Observatory (ESO) in 1998 and 1999 found that geometric foreshortening perfectly accounted for the change in Loki Patera’s intensity with emission angle (Marchis et al., 2001). However, this result relied on a comparison between data taken on dates separated by months, despite Loki Patera’s high intrinsic variability. If data points are only compared with other observations from the same night, the consistency of the dataset with a geometric foreshortening cosine law is less clear.

5.4. Resurfacing Mechanism

The analysis presented here has assumed the overturning-magma-sea mechanism for brightening events at Loki Patera. However, models such as resurfacing by lava flows are not ruled out. Here we discuss a few points related to the different potential scenarios for activity at Loki Patera; a more complete treatment of these scenarios, including their consistency with past observations, can be found in Matson et al. (2006).

The observed rate of cooling requires a mechanism whereby the magma body, whether a flow or a lake, does not cool to the point of solidification between brightenings. Complete solidification would cause a sharp drop in the intensity from the patera when latent heat ceases to be a source of heat flow (Settle 1979); such a drop is not seen in the observations. A 10-m thick lava flow with *Standard* thermal properties would take around a year to solidify completely (Davies et al. 2005), which is close to the amount of cooling time between overturns. The lack of detection of an intensity drop-off during cooling therefore cannot rule out resurfacing by lava flows of 10-m or

greater thickness.

Two features of Loki Patera’s activity that are explained by the overturn resurfacing mechanism are the regularity of the brightenings, and the nearly constant resurfacing rate across the southern part of the patera inferred from the smooth temperature distribution seen in *Galileo* observations (Spencer et al. 2000; Davies 2003; Howell and Lopes 2007). However, certain features of the 2013-2016 dataset seem to contradict aspects of the model. The multiple brightening phases required by the 2015-2016 event, as well as a possible reversal in the overturn direction, are inconsistent with a triggering mechanism in which instabilities in the oldest and thickest portion of the crust initiate overturn. A reversal in direction requires an overturn that is initiated at the youngest and hence most stable part of the crust. In addition, the average intensity of the 2015-16 brightening combined with its short duration is consistent with a model where only a portion of the patera is resurfaced. If brightenings are in fact due to an overturning magma sea, such a scenario would require an overturn that halts partway through.

Finally, the presence of two distinct hot spots in the southwest and southeast corners of the patera which are active outside of the nominal overturn phase, and the evidence from this analysis that Loki Patera emits more radiation during quiescent times than predicted by a cooling basaltic surface, suggest continuously-active regions. Although spacecraft detected activity only in the SW margin and not in the SE, earlier Keck data (de Pater et al. 2017) and high-resolution LBT data (Conrad et al. 2015) did see significant emission from the SE part of the patera at relatively quiescent times. If Loki Patera is indeed a magma sea being resurfaced by an overturning crust, the data are now of sufficiently high temporal and spatial resolution that a more complex model is required to match the observations.

5.5. Magma composition

Prior to the *Galileo* flybys, sulfur was believed to be the dominant magma composition on Io. Observations with the NIMS and SSI instruments on this spacecraft yielded high temperature measurements, ruling out a sulfuric composition and suggesting a basaltic or possibly ultramafic composition (e.g. McEwen et al., 1998; Lopes-Gautier et al., 2000; Lopes et al., 2004). The analysis presented here assumes a lake of basaltic composition, although other possible compositions have been proposed:

(1) *Sulfuric*: There is strong evidence from *Galileo* and ground-based observations that Loki Patera is not a sulfuric lava lake. The *Galileo* SSI instrument detected Loki Patera at wavelengths short of $1\ \mu\text{m}$ (McEwen et al., 1998) indicative of temperatures $>1000\ \text{K}$; two-temperature fits to *Galileo* NIMS observations of Loki Patera found high-temperature components above $900\ \text{K}$ (Davies et al., 2000); and observations of forbidden SO emission indicate vent temperatures near $1500\ \text{K}$ (de Pater et al., 2002), too hot for sulfuric magma. Using the Howell (1997) analytic cooling model, Rathbun and Spencer (2006) demonstrate that the calculated brightness assuming a sulfur lake is nearly three orders of magnitude too low to match the observations. The general characteristics of the 2013-2016 brightenings match those of previous years, leading to similar conclusions.

(2) *Ultramafic*: Magmas of ultramafic composition have different thermal properties from standard basalts. The differences that most impact the temperature and therefore thermal emission are in liquidus temperature

(1475 vs. 1900 K, for basaltic and ultramafic respectively); latent heat of fusion (4×10^5 vs. 8×10^5 J/kg), and specific heat (1500 vs. 1200 J/kg/K; values from Davies et al., 2005). The observations of the 2013 and 2014 events can be matched similarly well using these thermal properties, but require lower velocities (~ 0.6 km/day) and longer overturns (> 300 days), inconsistent with Loki Patera’s typical behavior. The apparently-good fits are likely due to the fact that the start time of these events are unconstrained. Matching the 2016 brightening with an ultramafic model requires resurfacing to cover only a very small fraction of the patera surface. In addition, these fits require a very short dim period which does not give the crust sufficient time to thicken to the point of instability. The ultramafic model predictions are thus less consistent with previous observations and other considerations, and the basaltic model is favored.

6. Conclusions

Near-infrared adaptive optics observations of Loki Patera were made at wavelengths of 2.3, 3.8, and 4.7 μm on 70 nights in 2013-2016 (de Kleer and de Pater, 2016). The period of observation covers three brightening events, which are analyzed here in the context of the Matson et al. (2006) model for Loki Patera as an overturning magma sea.

6.1. Magma Sea Model

The Matson et al. (2006) model for Loki Patera as an overturning basaltic magma sea provides a good fit to the observations of the 2013 and 2014 brightening events. The best-fit models find overturn propagation velocities of 1.2-1.5 km/day for these events, corresponding to resurfacing rates of 1500-1800 m^2/s . The results are not sensitive to the modeled patera geometry, and do not depend strongly on the continuity of the overturn (large rafts vs. continuous wave). The time-averaged thermal emission predicted by the model is ~ 8 TW with a peak power of 16-22 TW. This is consistent with NIMS observations, from which a minimum emission of 7.6 TW and a maximum of 17 TW were estimated (Davies et al., 2012). The 2016 brightening event appears to be more complex; a second brightening is seen during the nominal cooling phase, and fits to the data require a mechanism to reduce the modeled thermal emission during overturn. Models with modified lava thermal properties and models in which only a fraction of the patera is resurfaced fit these data equally well.

6.2. Interval between brightenings

The time intervals between successive brightenings depend on which thermal model is chosen, since observations during the early phases of the 2013 and 2014 brightenings are lacking. Models with *Standard* thermal properties find cycle durations of 440 ± 20 and 540 ± 20 days for the two events respectively, while models with *Modified* thermal properties find durations of 470 ± 20 days for both. For comparison, Loki Patera’s periodicity prior to 2001 was best fit with a period of 540 days, although variability in this interval was also present (Rathbun et al. 2002). Both sets of thermal properties predict a crust thickness around 6 meters at the beginning of overturn, although the crust thickness is slightly higher for models with *Standard* thermal properties. Rathbun et al. (2002)

estimate that solid crust overlaying magma with 10% bubbles will become gravitationally unstable at a thickness of 6 meters; the model predictions are therefore very consistent with gravitational instability as the mechanism triggering overturn. The future incorporation of the depth-dependent porosity into the thermal conduction would provide a more realistic and internally-consistent overturn model.

6.3. Decadal context

While brightening events at Loki Patera were observed consistently from 1987 through 2001 with a period around 540 days, bright activity may have shut off for several years beginning in 2002 (Rathbun and Spencer, 2006). Such a shut-off could be explained by small variations in the magma properties (Rathbun and Spencer, 2006). Brightenings at Loki Patera were again detected beginning in 2009 (de Pater et al., 2017), and brightening events since that time have had very similar characteristics (durations, intensities, and total power) to the pre-2002 activity. The most prominent difference is in the somewhat shorter interval between successive overturns despite similar bright-phase durations and derived propagation velocities.

6.4. Direction of Resurfacing

The source locations of the emission from within the patera indicate that resurfacing propagates in a clockwise direction, contrary to previous findings. This may indicate a reversal in propagation direction after 2002 or an overturn that is not well represented by a single, unidirectional wave. Past observations as well as new results presented here provide evidence for multiple overturn fronts and regions that remain continually active outside of the nominal overturn phase.

6.5. Topography

The intensity measured from Loki Patera is consistently low when viewed at high emission angle compared to the model as well as to measurements on the surrounding days. This indicates that the correction for geometric foreshortening is not accurately correcting for different viewing geometries. If this effect is due to a topographic shadowing of a uniformly-emitting patera (by mountains or the edge of the depressed patera), the height of the feature would need to be greater than 10 km, which is inconsistent with *Galileo* observations. Models in which the majority of emission comes from within 500 m of the patera edge are able to match the observation with a magma level only 100 m below the patera edge, but are qualitatively at odds with aspects of the overturn model. If the effect is due to shadowing of cracks which emit the majority of the radiation, the cracks must be ~ 3 times as wide as they are deep to match the observations.

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