

MEASURING IONIAN LAVA ERUPTION TEMPERATURES VIA VNIR COLOR IMAGING. L. P. Keszthelyi¹ and A. S. McEwen², ¹USGS Astrogeology, Flagstaff, AZ 86001 (laz@usgs.gov), ²Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721.

Introduction: One of the key unknowns about Io is the degree of melting of its interior [1]. The answer is essential to understanding how tidal heating operates in this volcanically active moon of Jupiter. This, in turn, has major implications for tidal heating in general, but especially for Europa and Ganymede. If the melting within Io is high enough to maintain a current magma ocean, insights into how the early Earth and Moon operated may also be waiting from intrepid Io explorers.

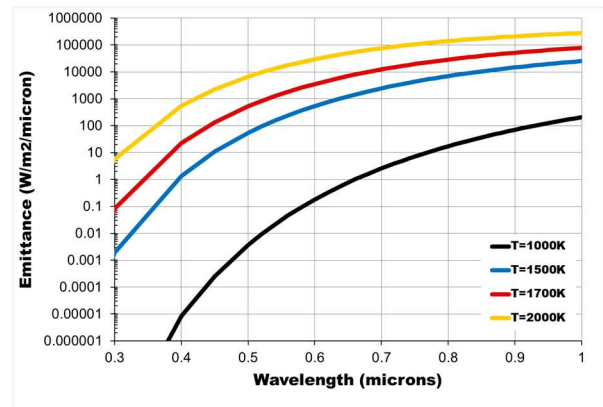
There are many geophysical methods to test for a magma ocean within Io [1], but here we consider using the temperature and composition of the erupting lavas. The composition of solidified lavas can be estimated using thermal infrared remote sensing [2,3]. For Io, ultramafic eruptions (i.e., >1700 K) would point to melt fractions >20% and allow a global magma ocean while basaltic temperatures (i.e., <1500 K) would be consistent with <10% partial melting and no magma ocean [4,5]. Here we focus on the problem of determining the temperature of the erupting lava to within ± 100 K as required to make this distinction.

Previous Work: Lava eruption temperatures were estimated using *Galileo* observations using both the Solid-State Imager (SSI) and Near-Infrared Mapping Spectrometer (NIMS) suggesting at least one eruption of lavas ~ 1800 K [6]. However, the uncertainties are too large to confidently differentiate between mafic and ultramafic temperatures [5,6]. The question of how to improve over the *Galileo* results has been investigated in some detail over the past two decades.

With lava flows even 1 mm/pixel imaging is insufficient to resolve fresh liquid lava flow surfaces [7], placing a premium on lava fountains and skylights that expose large areas of lava at near the eruption temperature [5,8]. Lava fountains have been observed repeatedly on Io but pyroclasts cool extremely rapidly, requiring temperature data to be collected within a 0.1 s window [5,9]. Lava tubes have been inferred on Io [10,11] and temperatures at skylights are stable for days or more [9]. This previous work establishes some key requirements for future measurements of Ionian lava temperatures but is incomplete.

New Analysis: Due to the shape of the Planck Function, the temperature is well-constrained by measuring just the slope of the short-wavelength side of the spectrum. For temperatures in the 1500-1700 K range, this requires data at least two wavelengths in the 0.5-1 μm range (Figure 1). It is desirable to be able to measure temperatures over the wider range of 1000-2000 K.

Figure 1. Planck Function with emissivity = 1.0.



For this investigation, we test if a set of colors (Table 1) selected for other imaging science needs will also work well for measuring lava temperatures.

Table 1. Baseline Io/Jupiter imaging science bandpasses.

Filter	Band (nm)	Primary/driving uses
CLR	300-1050	Closest-approach imaging
NUV	300-380	Plumes, SO ₂ auroral emissions
BLU	400-480	Surficial and plume SO ₂
GRN	500-560	Surface imaging
590	588-590	Sodium auroral emissions
ORG	600-640	Sulfurous flows
RED	660-710	Sulfurous plume deposits
727	730-740	Jupiter methane filter
756	750-770	Jupiter continuum filter
800	810-870	Pyroxene Fe-content
889	880-895	Jupiter methane filter
900	890-960	Pyroxene Fe-content
1MC	970-1000	Pyroxene Fe-content

To calculate signal-to-noise (SNR), we focus on a camera system similar to EIS onboard *Europa Clipper* [12] in terms of detector and optical performance and a mission like the *Io Observer* recommended by the decadal survey [13] or the *Io Volcano Observer* concept under study for Discovery [14]. This means a Jupiter orbiter that conducts high-speed flybys of Io. Such a mission provides the opportunity for regional mapping from a polar perspective at 100-500 m/pixel and local imaging of a few lower-latitude targets at 5-50 m/pixel. We expect lava fountains to fill at least one pixel but a 25 m² skylight will only fill 0.01% of a pixel at 500 m/pixel. The linetime is dictated by the spacecraft groundspeed near closest approach but can be selected by adjusting spacecraft roll rate further out.

Shot noise is calculated as the square root of the signal while read and quantization noise is set to 11 e⁻/pixel. Radiation noise is estimated in two different ways. The first uses the methods of [15] with the noise

accumulating at 3800 e⁻/s which is close to 10 times what *Galileo* SSI experienced. The second uses the method adopted by the EIS team, considering the 95% confidence limit on the contribution of radiation to the signal in any given pixel. At this probability, the chances that radiation hits at the corresponding locations in image data from two different bands will be mistaken for a hotspot is negligible. This model suggests lower noise at very short linetimes (≤ 1 ms) but a steep increase at longer linetimes, reaching ~ 1000 e⁻ at 50 ms.

Color ratios were computed by considering the Planck Function flux at 0.01 μm wavelength intervals passing through the optics and filters and onto the detector. The uncertainty in the resulting ratios shown in Table 2 was estimated by applying 1σ of noise to the value in the numerator and another 1σ to the value in the denominator.

Conclusion: The filter set driven by other science needs will also meet the requirements to measure lava temperatures at Io, assuming an EIS-derived imaging system. For example, the CLR/1MC and the ORG/GRN ratios are capable of distinguishing mafic and ultramafic lavas in distant and close observations, respectively. In

the more realistic scenarios there are sufficient data to do better than to assume an isothermal hot area within the pixel, allowing for more confident estimation of eruption temperatures.

References: [1] de Kleer K. et al. (2019) https://www.kiss.caltech.edu/final_reports/Tidal_Heating_final_report.pdf. [2] Kahle A. B. et al. (1988) *JGR*, 93, 15239-15251. [3] Greenhagen B. T. et al. (2010) *Science*, 329, 1507. [4] Williams D. A. et al. (2001) *JGR*, 106, 33105-33119. [5] Keszthelyi L. et al. (2007) *Icarus*, 192, 491-502. [6] McEwen A. S. et al. (1998) *Science*, 281, 87-90. [7] Vaughan R. G. and Keszthelyi L. (2012) *AGU Fall Meeting*, V21B-2772. [8] Davies A. G. et al. (2016) *Icarus*, 279, 266-278. [9] Davies A. G. et al. (2011) *GRL*, 38, L21308. [10] Keszthelyi L. et al. (2001) *JGR*, 106, 33025-33052. [12] Turtle E. P. et al. (2019) *LPSC 50*, Abstract #3065. [13] NRC (2011) *Visions and Voyages for Planetary Science in the Decade 2013-2022*. [14] McEwen A. S. et al. (2020) *LPSC 51*, Abstract #1648. [15] Klaasen K. et al. (1984) *Opt. Eng.*, 23, 334-342.

Table 2. Analysis for some select scenarios with radiation noise calculated following Klaasen [15] (above) and at a radiation level that <5% of pixels will exceed (below). “--” indicates that at least one band was saturated or had an SNR below 50. Entries in grey indicate conditions where the uncertainties in the ratio translate into larger than 100K uncertainties in the lava temperature

Target	Temp.	Resolution	TDI	Linetime	Unsaturated Bands w/ SNR >50	CLR/1MC	ORG/GRN
Fountain (1 km ²)	1000 K	5 m/pix	2	0.38 ms	CLR	2.28±0.05	9.36±5.33
Fountain (1 km ²)	1500 K	5 m/pix	2	0.38 ms	GRN, ORG, RED, 727, 756, 889	--	3.40±0.04
Fountain (1 km ²)	1700 K	5 m/pix	2	0.38 ms	BLU, GRN, 590, ORG, 727, 889	--	2.65±0.01
Fountain (1 km ²)	1000 K	500 m/pix	14	1.11 ms	CLR, 800, 900, 1MC	2.28±0.01	9.36±5.62
Fountain (1 km ²)	1500 K	500 m/pix	14	1.11 ms	GRN, 590, ORG, RED, 727, 756, 889	--	3.40±0.01
Fountain (1 km ²)	1700 K	500 m/pix	14	1.11 ms	BLU, GRN, 590	--	--
Skylight (25 m ²)	1500 K	10 m/pix	2	1.11 ms	ORG, RED, 727, 756, 889	--	3.40±0.07
Skylight (25 m ²)	1500 K	50 m/pix	2	1.11 ms	CLR, 800, 900, 1MC	3.90±0.04	3.40±3.11
Skylight (25 m ²)	1500 K	100 m/pix	14	50 ms	CLR, RED, 756, 800, 900, 1MC	3.90±0.01	3.40±15.9
Skylight (25 m ²)	1500 K	500 m/pix	14	50 ms	CLR	3.90±0.13	3.40±3.19
Skylight (25 m ²)	1700 K	500 m/pix	14	50 ms	CLR, 800, 900, 1MC	4.70±0.05	2.65±1.29
Target	Temp.	Resolution	TDI	Linetime	Unsaturated Bands w/ SNR >50	CLR/1MC	ORG/GRN
Fountain (1 km ²)	1000 K	5 m/pix	2	0.38 ms	CLR, 1MC	2.28±0.04	9.36±5.53
Fountain (1 km ²)	1500 K	5 m/pix	2	0.38 ms	GRN, ORG, RED, 727, 756, 889	--	3.40±0.03
Fountain (1 km ²)	1700 K	5 m/pix	2	0.38 ms	BLU, GRN, 590, ORG, 727, 889	--	2.65±0.01
Fountain (1 km ²)	1000 K	500 m/pix	14	1.11 ms	CLR, 800, 889, 900, 1MC	2.28±0.01	9.36±7.18
Fountain (1 km ²)	1500 K	500 m/pix	14	1.11 ms	GRN, 590, ORG, RED, 727, 756, 889	--	3.40±0.01
Fountain (1 km ²)	1700 K	500 m/pix	14	1.11 ms	BLU, GRN, 590	--	--
Skylight (25 m ²)	1500 K	10 m/pix	2	1.11 ms	GRN, ORG, RED, 727, 756, 889	--	3.40±0.04
Skylight (25 m ²)	1500 K	50 m/pix	2	1.11 ms	CLR, 800, 900, 1MC	3.90±0.03	3.40±0.50
Skylight (25 m ²)	1500 K	100 m/pix	14	50 ms	RED, 756, 800, 889, 900, 1MC	3.90±0.01	3.40±0.60
Skylight (25 m ²)	1500 K	500 m/pix	14	50 ms	--	3.90±0.22	3.40±2.71
Skylight (25 m ²)	1700 K	500 m/pix	14	50 ms	CLR	4.70±0.08	2.65±4.00