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Note

Charting thermal emission variability at Pele, Janus Patera and Kanehekili Fluctus with the *Galileo* NIMS Io Thermal Emission Database (NITED)

Ashley Gerard Davies [a,*], Glenn J. Veeder [b], Dennis L. Matson [a], Torrence V. Johnson [a]

[a] *Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA*
[b] *Bear Fight Institute, 22 Fiddlers Road, Winthrop, WA 98862, USA*

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ABSTRACT

Using the NIMS Io Thermal Emission Database (NITED), a collection of over 1000 measurements of radiant flux from Io's volcanoes (Davies, A.G. et al. [2012]. Geophys. Res. Lett. 39, L01201. doi:10.1029/2011GL049999), we have examined the variability of thermal emission from three of Io's volcanoes: Pele, Janus Patera and Kanehekili Fluctus. At Pele, the 5-μm thermal emission as derived from 28 night time observations is remarkably steady at 37 ± 10 GW μm^{-1}, reaffirming previous analyses that suggested that Pele an active, rapidly overturning silicate lava lake. Janus Patera also exhibits relatively steady 5-μm thermal emission (≈20 ± 3 GW μm^{-1}) in the four observations where Janus is resolved from nearby Kanehekili Fluctus. Janus Patera might contain a Pele-like lava lake with an effusion rate (Q_F) of ≈40–70 $m^3 s^{-1}$. It should be a prime target for a future mission to Io in order to obtain data to determine lava eruption temperature. Kanehekili Fluctus has a thermal emission spectrum that is indicative of the emplacement of lava flows with insulated crusts. Effusion rate at Kanehekili Fluctus dropped by an order of magnitude from ≈95 $m^3 s^{-1}$ in mid-1997 to ≈4 $m^3 s^{-1}$ in late 2001.

1. Introduction

The volcanoes of Io offer insight into the geophysical nature of this jovian satellite. As such, they are important observational targets for missions to the Jupiter system and also for ground-based telescopes (see summary in Davies (2007); see also de Pater et al., 2004; Lopes-Gautier et al., 1997; Marchis et al., 2005; McEwen et al., 1997; Veeder et al., 1994).

We are examining the variability of volcanic heat flow at local, regional and global scales using primarily *Galileo* Near Infrared Mapping Spectrometer (NIMS) data, adding to previous time-series analyses of Pillan and Pele (Davies et al., 2001), and the full NIMS datasets for Prometheus (Davies et al., 2006), Tupan Patera, Culann and Zamama (Davies and Ennis, 2011) and Loki Patera (Davies et al., 2012; Rathbun and Spencer, 2006). By examining thermal emission variability we better understand the role of volcanism in removing heat from the Io's interior and the surface expressions of volcanic activity. In order to identify individual eruption episodes and style of activity we have quantified thermal emission at 5 μm (4.7 μm after 11 October 1997) for every hot spot observed by *Galileo* NIMS. Using the NIMS Io Thermal Emission Database (NITED) (Davies et al., 2012), we now describe the variability of thermal emission from three hot spots on Io that were observed multiple times: Pele and Janus Patera (possible silicate lava lakes) and Kanehekili Fluctus (possible silicate lava flows).

2. NIMS observations of Io

NIMS was an instrument well-suited to observing thermal emission from ongoing or recent volcanic activity (Davies, 2007; Davies et al., 2010). Volcanic hot spots were counted by Lopes et al. (2004). The acquisition and processing of NIMS data of volcanic thermal emission, and descriptions of "tube" and "cube" products, are described in detail in Davies (2007) and references therein, but can be summarized as follows. NIMS observations consisted of data at 8–408 wavelengths between 0.7 and 5.3 μm obtained over a wide range of spatial resolutions until 11 October 1999, after which the number of wavelengths was limited to 12 or 15 distributed from ~1 μm to 4.7 μm. Raw radiance data of Io as 190 NIMS tube products were collected between June 1996 and October 2001. Some of these tube products contained multiple observations of Io. For example, the C9INWARMCV01 observation obtained on 27 June 1997 imaged the Janus/Kanehekili region nine times. Tube products were corrected for the instrumental spatial response and processed into 181 re-navigated and re-sampled cube products. Both are useful because "tubes" yield the most accurate radiant flux data, whereas "cubes" yield the most accurate navigation and location data. We examined all NIMS products and determined 5-μm radiant flux for all hot spot detections, collating the data into the NIMS Io Thermal Emission Database (NITED), which is described in Davies et al. (2012).

3. NIMS Io Thermal Emission Database

We have used all appropriate NIMS observations of Pele, Janus Patera and Kanehekili Fluctus to examine style and variability of volcanic activity. Where necessary, cube products were used to obtain accurate locations of thermal sources. We calculated radiant flux at ≈5 μm wherever possible, and at 4.6967 μm for observations obtained on and after 11 October 1999. Data were corrected for incident sunlight, where necessary, and a cosine correction was used as a correction for emission angle foreshortening (e.g., Davies et al., 2001).

4. Pele

Pele (255.7°W, 18.4°S) is a feature of particular interest because it is the only volcano on Io that, in every usable NIMS observation, displays a thermal emission spectrum similar to those of terrestrial active, overturning lava lakes (Davies et al., 2008, 2010; Davies et al., 2011). Pele has been identified as a hot spot in every appropriate observation by *Voyager* (Carr, 1986), *Galileo* NIMS (Davies et al., 2001) and SSI (e.g., Keszthelyi et al., 2001; McEwen et al., 1998; Radebaugh et al., 2004), *Cassini* (Radebaugh et al., 2004), *New Horizons* (Spencer et al., 2007) and ground-based telescopes (e.g., de Pater et al., 2004; Marchis et al., 2002, 2005;

* Corresponding author. Address: Jet Propulsion Laboratory, 4800 Oak Grove Drive, MS 183-401, Pasadena, CA 91109, USA.

E-mail address: Ashley.Davies@jpl.nasa.gov (A.G. Davies).

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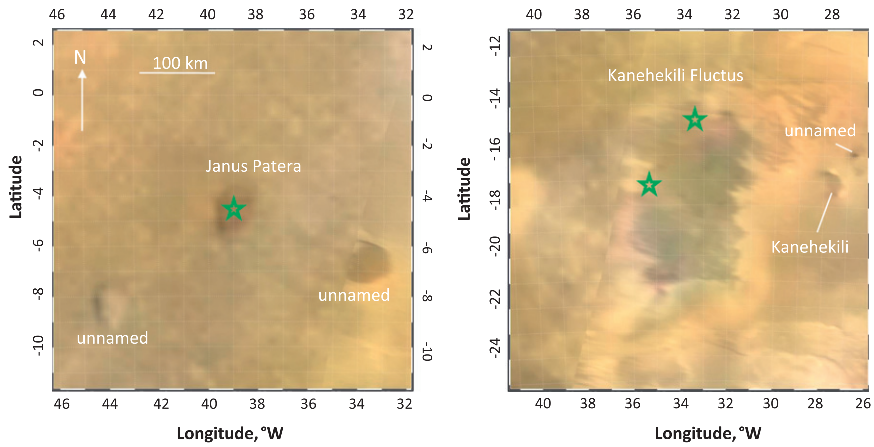

Fig. 1. (Left) Janus Patera (39°W, 15°S) and (right) Kanehekili Fluctus (33.6°W, 18°S). These images are clipped from the USGS Io Global Mosaic (Becker and Geissler, 2005) using the methodology of Veeder et al. (2011). Green stars denote the position of hot spots (>700 K) detected by *Galileo* SSI. Hot areas derived from NIMS data (Table 2) cover only a small portion of each feature. Janus Patera has an area of ≈1300 km^2. Kanehekili Fluctus has a dark area of ≈16,500 km^2. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
NIMS observations where Janus Patera and Kanehekili Fluctus are resolved.

Observation	Date, time (UT) (mm/dd/yy) (hh:mm)	Range (km)	Resolution (km pixel^{-1})	Emission angle, *e* (°)	Wavelength, λ (μm)	5-μm (4.7-μm after 11 October 1999) radiant flux (GW μm^{-1})	Comments
Janus Patera							
10INTHRMAL02A	9/19/97 0:58	343,916	172	80.0	4.9951	19.86	High emission angle; night
30INECLPSE01A	5/23/01 13:26	382,118	191	50.4	4.6967	14.91	Night observation
30INGLOBAL01A	5/23/01 17:40	342,507	171	46.1	4.6967	22.40	Day observation
30INGLOBAL01A	5/23/01 17:47	343,028	172	46.1	4.6967	20.72	Day observation
Kanehekili Fluctus							
C9INVOLCAN01	06/27/97 21:37	656,749	328	73.8	4.9951	63.24	High emission angle; night
10INTHRMAL02A	9/19/97 0:58	343,807	172	86.4	4.9951	52.04	High emission angle; night
12INHRSPEC01A	12/16/97 14:15	515,577	258	67.9	4.9703	41.35	Night observation
30INECLPSE01A	5/23/01 13:27	382,422	191	57.4	4.6967	5.37	Noisy – very faint thermal source
30INGLOBAL01A	5/23/01 17:40	342,876	171	53.1	4.6967	6.18	Day observation
30INGLOBAL01A	5/23/01 17:48	343,119	172	53.1	4.6967	7.11	Day observation

Veeder et al., 1994). Pele's fixed location, derived temperatures in excess of 1400 K, persistent plume deposits, and persistent activity all point to it being a lava lake in which the surface is constantly being disrupted by the explosive expansion of volatiles that have exsolved from ascending magma (see review in Davies, 2007).

5. Kanehekili Fluctus and Janus Patera

NITED has many examples of pairs of hot spots that are only rarely resolved due to the low spatial resolution of the NIMS data (although these observations still allow regional volcanic heat flow to be quantified). One example of such a hot-spot pair is Kanehekili Fluctus and Janus Patera. Kanehekili Fluctus (33.6°W, 18°S) is a lava flow field covering ≈34,500 km^2 (Williams et al., 2011) with the darkest and presumably most recently-emplaced areas of the fluctus totaling ≈16,500 km^2. Janus Patera (39°W, 4.5°S) has a floor area of ≈1600 km^2. These two volcanoes are located on Io's sub-jovian hemisphere about 450 km apart. The Janus/Kanehekili region (Fig. 1) was not imaged at high spatial resolution by *Galileo* or *Voyager* cameras. Two hot spots were detected at Kanehekili Fluctus by the *Galileo* Solid State Imaging experiment (SSI) (Kanehekili N at 33.4°W, 14.5°S and Kanehekili S at 35.5°W, 17.2°S) on numerous *Galileo* orbits (Keszthelyi et al., 2001; McEwen et al., 1998) as well as an active plume originating in the Kanehekili/Kanehekili Fluctus region that was observed by *Galileo* SSI in May 1997 and November 1997 (Geissler and McMillan, 2008). From SSI data, modeled hot spot areas in excess of 1000 K ranged from ∼0.8 km^2 to >6.4 km^2 (McEwen et al., 1998). Kanehekili Fluctus is also of particular interest as it was the site of a post-*Galileo* surface change detected by the *New Horizons* spacecraft in February 2007 (Coman and Phillips, 2011).

Janus Patera is an active hot spot that was often observed by SSI (Keszthelyi et al., 2001; McEwen et al., 1998), NIMS, and from the ground in late 2001 (de Pater et al., 2004; Marchis et al., 2005). The ground-based observations, obtained using Adaptive Optics (AO), showed an infrared spectrum with a preponderance of thermal emission at short infrared wavelengths (de Pater et al., 2004; Marchis et al., 2005). In terms of eruption style, volcanic thermal emission model (e.g., Davies et al., 2001) fits to these data suggested that Janus was the site of lava fountains, the early stages of an effusive eruption, or was an active, overturning lava lake (de Pater et al., 2004). We find that a full analysis of the NIMS dataset further constrains likely eruption style to that of an active lava lake.

Other features close to Janus Patera and Kanehekili Fluctus might also be the sites of thermal emission detected by NIMS in low-spatial-resolution data (see Fig. 1). A hot spot in May 2001 (*Galileo* orbit C30) NIMS data was reported to the southeast of Janus Patera (Lopes et al., 2004). However, having carefully examined the NIMS tube product, we conclude that this may be an artifact caused by instrument movement ("jitter") during data acquisition. Therefore, we do not include this in the data studied.

6. Data analysis

Most data were of the sunlit side of Io, but a few observations were obtained at night (Table 1). These spectra, unadulterated by incident sunlight, are fitted with a two-temperature, two-area thermal emission model (Davies et al., 1997) to calculate the total radiant thermal emission (Q_{rad}) from the active or recently active areas of the volcano under scrutiny (e.g., Fig. 2).

Radiant flux as a function of wavelength is found by fitting the corrected NIMS spectra with the function