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Charting thermal emission variability at Amirani with the *Galileo* NIMS Io Thermal Emission Database (NITED)

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ABSTRACT

We have examined the variability of thermal emission from lava flows at Amirani on Io, using measurements of radiant flux from detections by the *Galileo* Near Infrared Mapping Spectrometer (NIMS) between 1996 and 2001. Amirani is the longest currently active lava flow field in the Solar System and a persistent thermal source in every *Galileo* NIMS observation that covers its location. We have quantified the thermal emission from hot spots correlated with discrete areas of new lava flow emplacement at points along the length of the Amirani flow field in high spatial resolution NIMS observations in 2000 and 2001. Where discernible, the position of some effusive activity changes from orbit to orbit. We find the implied style of emplacement of lava at Amirani is consistent with pahoehoe-like flows. There is an estimated 50% decrease in discharge rate between 1997 and late 2001, perhaps linked to an outburst eruption in the Amirani vicinity in February 2001. The variability of thermal emission from Amirani is less than that seen at a number of other persistently active ionian volcanoes (such as Prometheus, Culann, and Loki Patera). All of these volcanoes exhibit large increases and decreases in the absolute magnitude of thermal emission (see Matson et al., 2006 [Loki Patera]; Davies, A.G. et al. [2006]. Icarus 184, 460–477 [Prometheus]; and Davies, A.G., Ennis, M.E. [2011]. Icarus 215, 401–416 [Culann]). At Amirani, as at these volcanoes, the thermal emission measured between 1996 and 2001 indicates a persistent, although variable, supply of magma to the surface. In high spatial resolution NIMS observations of hot spots obtained in 2000 and 2001 we estimate the emitted power from active lava flows associated with Amirani to be ~170 ± 30 GW, which corresponds to total effusion rates (assuming a basaltic composition) from multiple points along the Amirani flow of 34–56 m^3/s.

1. Introduction

Volcanoes offer insights into the geophysical nature of Io. As the surface manifestation of internal heating and volcanic advection, they are important observational targets for missions to the Jupiter system as well as for ground-based telescopes (see summary in Davies, 2007; see also de Pater et al., 2004; Lopes-Gautier et al., 1997; Lopes and Spencer, 2007; 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 data primarily from the *Galileo* Near Infrared Mapping Spectrometer (NIMS). This work adds to previous results from time-series analyses of Pillan (an episodic volcanic center where an outburst eruption emplaced voluminous, thick lava flows in 1997) and Pele (a persistent, active, overturning lava lake) (Davies et al., 2001), and the full NIMS datasets for Prometheus (Davies et al., 2006); Tupan Patera, Culann and Zamama (Davies and Ennis, 2011) (where resurfacing likely is dominated by pahoehoe-like flows with insulated crusts); Loki Patera (possibly a massive active lava lake that, generally, overturns quiescently) (Davies et al., 2012b; Rathbun and Spencer, 2006; Rathbun and Spencer, 2010); Janus Patera (another candidate for an active lava lake) and Kanehekili Fluctus (another active lava flow field) (Davies et al., 2012a). By examining and comparing thermal emission variability and eruption persistence at different hot spots we hope, ultimately, to understand the surface expressions of volcanic activity and the role of volcanism in removing heat from Io's interior. In order to identify individual eruption episodes and style of activity we have previously quantified thermal emission at 5 μm (4.7 μm after 11 October 1997) for

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every hot spot observed by *Galileo* NIMS (an effort described in detail below).

Using 44 NIMS observations of Amirani obtained between 1996 and 2001, as well as observations obtained by other *Galileo* instruments, we now describe the variability of thermal emission from the lava flow field at Amirani and estimate effusion rate. We also examine the effect of range to target and the presence of nearby hot spots in determining regional volcanic thermal emission.

2. *Galileo* NIMS observations and NITED

The NIMS instrument was well-suited to observing thermal emission from ongoing or recent volcanic activity (Davies, 2007; Davies et al., 2010, 2012b). The acquisition and processing of NIMS thermal emission data, and descriptions of "tube" and "cube" products, are described in Davies (2007) and references therein. NIMS observations consisted of data at 8–408 wavelengths between 0.7 and 5.3 μm obtained over a wide range of spatial resolutions. After the 11 October 1999 grating drive failure the number of wavelengths was limited to 12 or 15 distributed from ~1 μm to 4.7 μm. Raw Io radiance data were collected as 190 NIMS "tube products" between June 1996 and October 2001. Tube products were corrected (re-navigated and re-sampled) for the instrumental spatial response and processed into 181 "cube products". Both are useful because "tubes" yield the most accurate radiant flux data, whereas "cubes" yield the most accurate spatial data.

For the NIMS Io Thermal Emission Database (NITED), as described in Davies et al. (2012b), we examined all NIMS products and determined 5-μm radiant flux for all hot spot detections. 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.

For this study, we examined all NIMS observations of the Amirani region, augmenting our analysis with data obtained by the *Galileo* Solid State Imaging experiment (SSI) and Photo-Polarimeter Radiometer (PPR) to quantify the style and variability of thermal emission from Amirani during the *Galileo* era (1996–2001).

3. Amirani

Amirani was discovered as an active volcanic center through the identification of a volcanic plume by *Voyager 1* and *Voyager 2* in 1979 (Strom et al., 1981). During the *Voyager 1* encounter with Io the plume was seen to be between 65 and 137 km high, depending on the filter used. During the *Voyager 2* encounter four months later, the height of the plume was 53–114 km (Strom et al., 1981).

A plume at Amirani was observed at great distances by *Galileo* SSI from late 1996 through 1999 (Geissler and McMillan, 2008). This dust-rich plume, between 60 ± 17 and 87 ± 47 km in height, appeared to be the result of molten silicate lava interacting with surface ices. Such a style of plume generation has also been seen at other locations on Io, most notably Prometheus (Kieffer et al., 2000; McEwen and Soderblom, 1983; Milazzo et al., 2001).

A review of *Galileo* observations of the Amirani flow field was made by Davies (2007). The Amirani lava flow field (115°W, 24°N) (Fig. 1) covers over 25,000 km^2 (Veeder et al., 2009, 2012). At over 300 km long, and with an average width of 60 km, it may be the longest active new lava flow field in the Solar System (Keszthelyi et al., 2001) and as such is of particular interest in regard to its long-lived supply of magma. Early in the *Galileo* mission, Amirani was identified as a hot spot from both SSI (McEwen et al., 1997) and NIMS data (Lopes-Gautier et al., 1997). Surface temperatures and temperature profiles along the flow field were estimated by Lopes et al. (2001, 2004) from NIMS data collected in late 1999 and early 2000.

Our review of data in NITED shows that an Amirani hot spot was detected in every appropriate NIMS observation. The NIMS data suggested a power output of 327 GW (Davies, 2003; Davies and Ennis, 2011) from a two-component ("two-temperature, two-area") model fit to a NIMS nighttime spectrum from observation g1i003tr which was obtained on 28 June 1996 (*Galileo* orbit G1). This model indicates a relatively small high-temperature (in excess of 1100 K) source and a larger lower-temperature region of activity. Such high temperatures derived from NIMS data are an indicator of silicate volcanism. Silicate volcanism on Io is also supported by the detection by SSI of visible emission from several other very hot areas (>1000 K) at night and in eclipse (McEwen et al., 1997, 1998).

The shape of the thermal emission spectrum of the entire flow field in the low spatial resolution NIMS data suggests that the dominant style of emplacement at Amirani is that of lava flows with insulated crusts (Davies et al., 2000). This proposition is consistent with the appearance of new lava flows in *Galileo* SSI daytime images. In particular, Keszthelyi et al. (2001) identified 620 km^2 of new flows emplaced by 23 breakouts within the Amirani field between November 1999 and February 2000.

The locations of the flows in the 22 February 2000 SSI I27 data (the low albedo areas within the Amirani field in Fig. 1a) correspond to the locations of thermal anomalies detected by NIMS in observation 27i001cr, also obtained on 22 February 2000. The NIMS thermal sources are shown in Fig. 1b. We designate these areas 1 through 5, from north to south along the lava flow field.

Another notable observation of Amirani was obtained by NIMS on 6 August 2001 (observation 31i001: Fig. 1c) which showed three distinct areas of thermal emission along the length of the flow field. We designate these A, B and C, from north to south along the flow field.

Veeder et al. (2009, 2012) estimated that the thermal emission from the entire lava flow field was 399 GW in 2001. This estimate was derived by assigning an effective temperature of 129 K (the temperature of the Lei-Kung Fluctus flow field) to the entire 25,400 km^2 Amirani flow field as a first order estimate. Below, we refine this estimate of thermal emission by combining the SSI-derived new flow areas in February 2001, the energy from these areas as measured by NIMS, and the thermal emission from the older larger flow surfaces as determined from PPR scans (Rathbun and Barrett, 2007; Rathbun et al., 2004). This extends our work on quantifying the thermal emission from all of Io's volcanoes (Veeder et al., 2009, 2011, 2012, 2014).

Amirani is also often visible in ground-based telescope observations. Amirani was the location of a large thermal event observed using the Keck telescope (Mauna Kea, Hawai'i, USA) and utilizing adaptive optics (AO), on 22 February 2001 (Marchis et al., 2002). The event was apparently located in the middle of the lava flow field, and roughly in the position at or to the west of source 4 in Fig. 1b. Marchis et al. (2002) estimated that the thermal emission from this short-lived event was ~5.5 TW, with a temperature of ~990 K and an area of ~100 km^2. When *Galileo* SSI imaged this area in October 2001, there was little residual evidence of this event. The short-lived February 2001 outburst eruption was an anomaly in the otherwise relatively steady thermal emission at Amirani throughout the *Galileo* era.

We are interested in determining the instantaneous lava volumetric effusion rate (Q_{eff}, m^3/s) at Amirani. To do so requires isolating the active, or recently active, areas of lava flows within the older field. Although much of the thermal emission at Amirani comes from cooling surfaces at a temperature of around 130 K that are not detectible as thermal sources by NIMS, NIMS is very