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Variability and geologic associations of volcanic activity in 2001–2016

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ABSTRACT

Since the end of the *Galileo* epoch, ground-based observations have been crucial for the continued monitoring and characterization of volcanic activity on Jupiter's moon, Io. We compile and analyze observations from the Keck and Gemini North telescopes between 2001 and 2016, including new and published observations from 2003, 2004, 2005, 2007, 2008, 2009, 2011, 2012, 2013, and 2016. A total of 88 distinct hot spot sites were detected over the 15-year period, 82 of which were detected multiple times, and 24 of which were not detected by *Galileo* at thermal infrared wavelengths (1–5 µm). A variety of analytical methods are utilized to investigate the detections of active volcanism as a surface expression of interior heating. Geologic associations of hot spots, including patera type, lava flow type, and proximity to mountainous regions, are made using the USGS-published global geologic map of Io (Williams, 2011). We also provide a summary of outburst-scale events, along with the slightly less bright but more frequent, mini-outbursts described by de Kleer and de Pater (2016a).

We investigate the spatial distribution of volcanic activity on Io using nearest neighbor, mean pairwise spacing, and mean latitude statistics with various classification schemes. The analysis confirms previous findings in that the heat dissipation appears to be primarily concentrated in the asthenosphere resulting in a high time-averaged surface heat flux at low latitudes. Our observations show significant spatial deviations do exist from the asthenosphere heat dissipation model while also suggesting a deeper source of magma ascent to be present as well, supporting conclusions from previous analyses of primarily spacecraft data (Veeder et al., 2012; Hamilton, 2013; Davies et al., 2015). From a temporal perspective, there are signs of significant variations in the distribution of global heat flux, as volcanoes undetected, and probably dormant, during the *Galileo* encounters subsequently erupted and remained active during our observations. We also use the on 3.8-µm radiant intensity timelines of individual hot spots, along with the distribution of extensive lava fields in relation to detected activity, as a means to investigate possible connections between hot spots and short timescale, spatio-temporal variations in the global heat flux distribution. We conclude that while the global heat flux distribution remains relatively constant over decadal timescales, there is evidence that significant deviations do occur potentially as a result of mountain forming processes or triggering mechanisms between eruptions.

1. Introduction

The prolific volcanic activity on Jupiter's moon, Io, has been a well-documented phenomenon since the first surface images provided by the *Voyager* mission (Smith, 1979). The global heat flow of Io, calculated to be between 1.9 and 2.6 W/m^2 (Matson et al., 1981; Veeder et al., 1994; 2012), is most likely a result of tidal heating resulting from Io's forced eccentric orbit around Jupiter (Peale et al., 1979). The heat transfer from this tidal forcing occurs primarily through advection, spurring the high-rate of volcanism observed at the surface.

The *Galileo* mission provided the first detailed view of Io's volcanism over a five-and-a-half-year period beginning in June 1996. Among many valuable insights, the imagery and data

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acquired from the Solid-State Imager (SSI) (Belton, 1992), Near-Infrared Mapping Spectrometer (NIMS) (Carlson et al., 1992), and Photopolarimeter–Radiometer (PPR) (Russell, 1992) demonstrated the wide variety and high variability of eruptions on Io, while also providing a never before seen view into the surface geology associated with these eruptions. Since *Galileo*, ground-based observations have added to the timeline of Io's volcanic activity. Using the Keck and Gemini North telescopes coupled with adaptive optics, we can resolve individual eruptions on the surface of Io in the near-infrared, enabling us to continue monitoring the characteristics and locations of hot spots from the ground.

We present near-infrared adaptive optics observations of Io obtained between 2001 and 2016, some of which were previously published (Marchis, 2005; de Pater, 2014a; 2016a; 2016b; de Kleer and de Pater, 2016b; 2016a). We analyze the spatial and temporal variability of the thermal detections in the adaptive optics dataset. We therefore add to the timeline of Io's evolving volcanic activity. Io displays a variety of eruption styles (e.g., Davies, 2007), but none more notable than the outburst-scale events, where the total radiance of Io in Ms-band (5 µm) doubles at the peak of the event (Blaney et al., 1995). A summary of these eruptions detected during the adaptive optics program, along with mini-outburst eruptions, is provided. Previous outbursts are summarized by Veeder et al. (2012) and references therein. We also investigate the geologic associations of the detections within the Io database, built in ArcGIS^{TM} and based on the United States Geological Survey (USGS)-published global geologic map (Williams, 2011). The Io database is a comprehensive digital source of the *Galileo* Io data and of several derived data products, and includes definitions and mapping of geological units such as paterae, lava flows, mountains, plains, and plume deposits. Establishing geologic associations with the detected hot spots provides crucial information towards understanding Io's volcanism and geophysics.

In Section 2, we describe our analysis methodology, including photometry, single-temperature blackbody fits, image navigation, geologic associations and spatial statistics. Beginning in Section 3, we provide a general summary of the data obtained between 2001 and 2016 and focus on the temporal variations in hot spot detections and calculate the total Lp-band (3.8 µm) intensity and power output from hot spots from each period of observation. We also investigate the spatial distributions and geologic associations of the detected hot spots, which include calculation of the global power output from hot spots as a function of both longitude and latitude. In Section 4, we compare the hot spot activity with the activity observed during the *Galileo* mission. We also compare our observations with the heat flow distribution predicted by current tidal heat dissipation models. Section 5 presents a summary of our conclusions.

2. Observations and analysis methods

2.1. Observations

The data used in our analysis were obtained between 2001 and 2016, with a total of 14 distinct datasets (Table 1). A dataset is loosely defined as a set of observations performed within the same year and in close succession, ideally providing full longitudinal coverage of Io. All observations are ground-based, using adaptive optics on the 10-m Keck II and 8-m Gemini North telescopes, where we use the NIRC2 and NIRI imagers, respectively, with exception of *New Horizons* data provided in Tsang et al. (2014). Along with the data presented in Tsang et al. (2014), we also included data previously provided by Marchis (2005), de Pater (2014a, 2016a, 2016b), and de Kleer and de Pater (2016b,a) corresponding to observations performed in 2001, 2010, 2013, and 2015, respectively. The rest of the observations taken in 2003, 2004, 2005, 2007, 2008, and 2009 have not been published in their entirety.

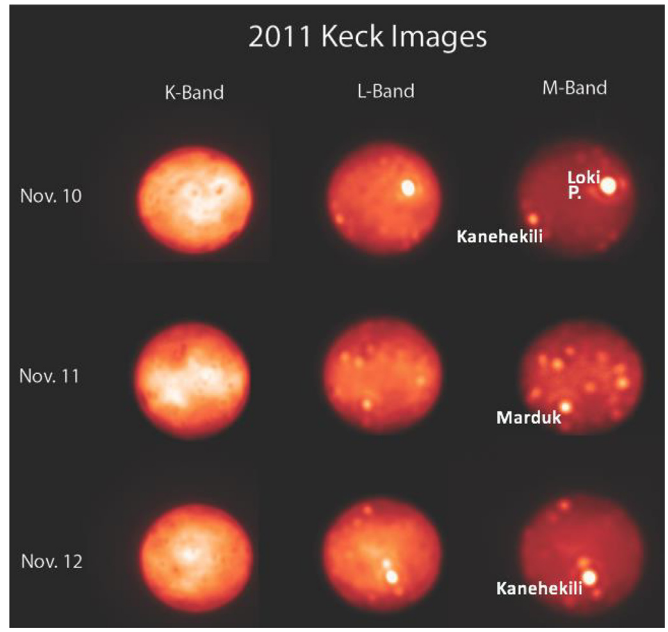

Fig. 1. Images of Io in November of 2011 taken by the 10-m W.M. Keck II telescope using adaptive optics at the wavelengths of 2.3, 3.8 and 4.7 µm. A majority of the thermal activity in the 2011 observation period was detected at wavelengths around 4 µm or longer with temperatures representative of primarily silicate volcanism. The central meridian longitude for Nov. 10, Nov. 11, and Nov. 12 ranged from 334°W–343°W, 194°W–195°W and 40°W–42°W, respectively, for the images shown. These images, along with the rest of the 2011 dataset, have not been published previously. In these images, Io North is up.

Various Near-IR filters were used, ranging from 1.02 µm to 4.67 µm, although only one eruption at Surt in 2001 (Marchis, 2002) was detected at wavelengths below the Kc-band filter centered at 2.27 µm. The narrow Kc-band (2.27 µm), broad Lp-band (3.78 µm), and broad Ms-band (4.67 µm) filters were used consistently in each dataset beginning in 2001. Beginning in 2011, the narrow-band H_2O, PAH, Br_α-continuum, and Br_α filters, corresponding to wavelengths of 3.06 µm, 3.29 µm, 3.99 µm, and 4.05 µm, respectively, were also used consistently for the observations thereafter. Table 1 provides a summary of all datasets and Fig. 1 shows several example images from 2011. Table 2 provides a summary of the filters used over the course of the program for the Keck and Gemini telescopes.

A distinction is made between the observations in 2001–2013 and those made in 2013–2016. Between 2001 and 2013 the observations of Io were sporadic and often occurred over just a handful of nights within a year. Table A1 in the Appendix lists all detections not previously published within this period. In contrast, between 2013 and 2016 a systematic, high-cadence program was implemented over 100 nights. The 2001–2013 observations can be viewed as a snapshot into yearly variability while the 2013–2016 observations provide a snapshot into daily to monthly variability.

2.2. Photometry and detection limits

We calculated the intensity of hot spots in each filter using aperture photometry, the methods of which are described in detail in de Pater (2014a, 2016a) and de Kleer and de Pater (2016b). On photometric nights, a standard star was used to flux calibrate the Io images. On non-photometric nights, Io's intensity was calibrated to the brightness of the disk, which is stable over time after correction for Io's geocentric and heliocentric distance. Foreshortening