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Spatial distribution of Io's volcanic activity from near-IR adaptive optics observations on 100 nights in 2013–2015

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ABSTRACT

The extreme and time-variable volcanic activity on Jupiter's moon Io is the result of periodic tidal forcing. The spatial distribution of Io's surface heat flux provides an important constraint on models for tidal heat dissipation, yielding information on interior properties and on the depth at which the tidal heat is primarily dissipated. We analyze the spatial distribution of 48 hot spots based on more than 400 total hot spot detections in adaptive optics images taken on 100 nights in 2013–2015 (data presented in de Kleer and de Pater [2016] Time variability of Io's volcanic activity from near-IR adaptive optics 13 observations on 100 nights in 2013–2015). We present full surface maps of Io at multiple near-infrared wavelengths for three epochs during this time period, and show that the longitudinal distribution of hot spots has not changed significantly since the *Galileo* mission.

We find that hot spots that are persistently active at moderate intensities tend to occur at different latitudes/longitudes than those that exhibit sudden brightening events characterized by high peak intensities and subsequent decay phases. While persistent hot spots are located primarily between ± 30°N, hot spots exhibiting bright eruption events occur primarily between 40° and 65° in both the northern and southern hemispheres. In addition, while persistent hot spots occur preferentially on the leading hemisphere, all bright eruptions were detected on the trailing hemisphere, despite the comparable longitudinal coverage of our observations to both hemispheres. A subset of the bright hot spots which are not intense enough to qualify as outburst eruptions resemble outbursts in terms of temporal evolution and spatial distribution, and may be outbursts whose peak emission went unobserved, or else scaled-down versions of the same phenomenon. A statistical analysis finds that large eruptions are more spatially clustered and occur at higher latitudes than 95% of simulated datasets that assume that eruptions occur at random and independent locations.

The preferential occurrence of bright, violent eruptions at higher latitudes supports the idea that a deeper magma source supplies these events, as has been previously hypothesized. The monotonic eastward progression of bright eruptions at southern latitudes from 300° to 200°W also suggests a possible eruption triggering mechanism operating across distances of ~500 km. A comparison to tidal heating models finds a good correspondence between recent models incorporating a partially-fluid interior (Tyler et al. [2015] Astrophys. J., 218–222). and hot spots in the leading hemisphere as well as persistent hot spots. However, hot spots on the trailing hemisphere and bright eruptions do not match these models well, corresponding better to standard deep-mantle heating models (Segatz et al. [1988] Icarus, 75, 187–206) although this match is still imperfect.

1. Introduction

An understanding of the interior properties and geophysics of rocky bodies in the Solar System is crucial for providing a framework in which to interpret observations of extrasolar planets. In cases of tidally-heated bodies with subsurface oceans such as Europa and Enceladus, models for how and where tidal heat is dissipated in planetary interiors are needed to answer questions about the presence and history of liquid water, which affects their long-term habitability. Such models would also help predict whether extrasolar planets might have volcanism, global magma layers, or even liquid water. However, a major challenge to understanding planetary interiors is the sparsity of information that can be

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obtained remotely, particularly without in situ gravity and magnetometer measurements.

Io represents a unique case where an interior process (tidal heating) manifests on the surface in a clearly detectable way, as extreme volcanic activity. This moon therefore provides a unique testbed for interior processes, tidal heat dissipation in particular. The distribution of heat flow on a planet's surface puts an important constraint on models of tidal heat dissipation, and in particular on how deep within the interior the heat is dissipated. Models show that if the heat is primarily dissipated in the deep mantle, Io's surface heat flux should be highest at the poles, and should be higher on the leading/trailing hemispheres (longitudes of 90° and 270°W) than on the sub- and anti-jovian hemispheres (longitudes of 0° and 180°W). In contrast, if the heat is primarily dissipated in a fluid asthenosphere, surface heat flux should be very low at the poles, reaching maxima around the sub- and anti-jovian points at ± 30° latitude, with secondary maxima at the equatorial leading and trailing points (Ross et al., 1990; Segatz et al., 1988). Io's true heat dissipation is likely a combination of these idealized scenarios, potentially with lateral convective flows that smooth out the surface heat flux pattern (Davies et al., 2015; Hamilton et al., 2013; Tyler et al., 2015).

Much recent progress has been made in characterizing the distribution of volcanic heat flow on Io, and on developing realistic tidal heating models that can be tested against observations. Previous work has assumed that the volcanic heat flow distribution on the surface can be used as a tracer of the distribution of internal heat flow. We follow this assumption, while noting that the connection between interior heating and its surface expression as volcanism has not been checked, and these properties may correlate imperfectly.

Early results from the *Galileo* mission found that there is a lower concentration of volcanic centers at high latitudes (Carr et al., 1998; Schenk et al., 2001), but that high latitude paterae are larger, suggesting a different eruption character (Radebaugh et al., 2001). Schenk et al. (2001) and Radebaugh et al. (2001) also noted a bimodal distribution of volcanic centers that peaks near 330°W and 150°W. Lopes et al. (2004) analyzed 166 volcanic centers observed by *Galileo* NIMS (78 at the highest resolution), and confirm that the distribution of active centers also has a peak at 150°W. In a series of recent papers, Veeder et al. (2009; 2011; 2012; 2015) identified additional faint emission sources in the NIMS dataset and characterized the thermal emission from ~250 total volcanic centers observed by *Galileo*. A heat flow map based on this analysis is presented in Davies et al. (2015), and indicates a non-uniform distribution of heat flow which is not a good match to any of the tidal heating model end-members. These authors note a lack of close correlation between density of volcanic centers and local heat flow. The clustering of hot spots and paterae on Io, as identified from the first global geologic map of Io (Williams et al., 2011) as well as from space- and ground-based observations, shows more uniformity and less randomness in equatorial regions compared to the poles. This suggests that volcanic centers are independently formed at high latitudes but that magma scavenging occurs in the near-equatorial region (Hamilton et al., 2013), consistent with a shallow magma source near the equator and a deeper source for eruptions at high latitudes.

All of the above authors identify an eastward offset of 30–60° in the concentration of volcanic activity from the locations predicted by heating models. In addition, the longitudes of the maxima based on active volcanism fall ~30° eastwards of the maxima based on paterae (Hamilton et al., 2013). In the first model to incorporate the fluid effects of a partially-molten interior layer, Tyler et al. (2015) demonstrate that the longitudinal offset can be explained by including the tidal response of a fluid layer such as the "magma ocean" implied by constraints derived from the *Galileo* magnetometer data (Khurana et al., 2011). They propose that high-latitude eruptions may be driven by deep-mantle heating, while equatorial volcanoes may have a shallow magma source. Such a scenario would imply hotter, more violent polar volcanoes occurring at random locations, while equatorial volcanoes may be cooler, less violent, and distributed more evenly due to competition for shallow magma reservoirs (Hamilton et al., 2013)

In a companion paper (de Kleer and de Pater, 2016), we present a new dataset of ground-based adaptive optics images of Io in the near-infrared, including 409 detections of activity from at least 48 distinct hot spots over a period from August 2013 through December 2015. The high cadence of our observations samples both transient and long-lived eruptions, and the number of detections is large enough to provide a statistical sample for an analysis of the spatial distribution of active centers. While the time-variability of hot spot emission is discussed in de Kleer and de Pater (2016), this article focuses on the spatial distribution of the detected hot spots. In Section 2 we summarize our observations. The spatial distribution of volcanic activity is presented in Section 3, including near-infrared surface maps for multiple epochs and wavelengths. Section 4 presents a statistical analysis of the distribution of large eruptions, and Section 5 discusses the implications of our results, including a comparison with patera and hot spot distributions determined by past work and an investigation of correlations between eruption characteristics and hot spot locations. Our main conclusions are summarized in Section 6.

2. Observations and data processing

The analysis in this paper is based on near-infrared (1–5 μm) images of Io obtained on 100 nights between August 2013 and December 2015 with adaptive optics at the Gemini N and Keck telescopes. The observations, data reduction, and analysis methods are described in a companion paper (de Kleer and de Pater, 2016), and the hot spot positions and intensities are listed in Table B.4 of that article. The reader is also referred to that paper for a detailed study of the uncertainties on the retrieved hot spot properties.

2.1. Projection and surface maps

The Keck data are projected with an equirectangular projection onto a grid of constant latitude and longitude intervals. Before projection, the images are deconvolved using the stellar point spread function (PSF) for each night of observation using the AIDA routine (Hom et al., 2007), in order to sharpen the images and enhance contrast. All images are corrected for limb darkening according to a Minnaert law:

$$I = I_0 \mu_0^k \mu^{k-1}, \quad (1)$$

where μ_0 is the cosine of the angle of incident sunlight, μ is the cosine of the emission angle[1], and k is an empirically-determined value between zero and one. The best correction is typically found for values of k between 0.65 and 0.75, in agreement with Laver and de Pater (2008) and de Pater et al. (2014). The effect of the limb-darkening correction at Kc-band is demonstrated in Fig. 1 before and after projection onto the rectangular grid.

The projected images within each of three observing epochs are stitched together to produce global maps in each filter. At longitudes which were observed on multiple nights, the map is the median-average of all available observations. Each observation is scaled so that the over-lapping regions on all nights match as well as possible, using the highest-quality image as a photometric reference. After applying the flux-calibration procedures described in

[1] Ephemeris from JPL HORIZONS System: ssd.jpl.nasa.gov/horizons.cgi