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Map of Io's volcanic heat flow

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ABSTRACT

We present a map of Io's volcanic heat flow. Io's high heat flow is a result of intense tidal heating, which generates widespread volcanic activity. The surface expression of ongoing volcanic activity constrains the location and magnitude of tidal dissipation within Io. Tidal heating models place heating either at relatively shallow (aesthenosphere) levels, or deep in the mantle. It was thought that actual tidal heating could be approximated using a combination of these end-member models. Io's volcanic heat flow has now been mapped in sufficient detail to compare with the models. Our maps show that the distribution of heat flow is not matched by current models of deep nor shallow tidal heating, nor by any combination of these two models. We find relatively low heat flow at sub-jovian (0°W) and anti-jovian (180°W) longitudes, at odds with the pure aesthenospheric heating model. Furthermore, there are large swaths of Io's surface where there is poor correlation between the number of hot spots in an area and the power emitted. We have previously accounted for ≈54% of Io's observed heat flow. We now show that Io's anomalously warm poles, possibly the result of heat flow from deep-mantle heating, would yield the "missing" energy (48 TW) if the polar surfaces are at temperatures of ∼90 K to ∼95 K and cover latitudes above ∼43° to ∼48° respectively. This possibility implies a ratio of deep to shallow heating of about 1:1. However, explaining regional variations in surface volcanic activity requires more detailed modeling of the location and magnitude of the internal tidal dissipation and the consequences of mantle convection and advection within Io. Future model predictions can be compared to our heat flow map.

1. Introduction

The jovian satellite Io has been known to be intensely volcanic since the *Voyager* 1 encounter in 1979, with tidal heating as the primary source of energy (Hanel et al., 1979; Peale et al., 1979; Smith et al., 1979; see Davies, 2007, for detailed history). The observed surface distribution of Io's heat flow should reflect the location and magnitude of tidal heating, as well as the mechanisms by which heat escapes from the interior. Testing the existing models of interior heating, the resulting volcanic advection, and the (observable) surface expressions of volcanic thermal emission first requires the quantification of heat flow from each of Io's volcanic centers. These quantifications of volcanic thermal emission for the years 1996–2001 were published in a series of papers (Veeder et al., 2009, 2011, 2012, 2015) that together yielded a snapshot of Io's volcanic activity during the *Galileo* epoch. These analyses primarily used data obtained by the *Galileo* Near Infrared Mapping Spectrometer (NIMS) (Carlson et al., 1992), the *Galileo* Photo-Polarimeter Radiometer (PPR) (Russell et al., 1992), and multi-wavelength infrared radiometry from large ground-based telescopes equipped with adaptive optics (AO) (e.g., de Pater et al., 2003, 2004; Macintosh et al., 2003; Marchis et al., 2000, 2005).

We now use these thermal emission data to map Io's volcanic heat flow, and compare this global map with the distributions expected for models of both deep and shallow heat sources (described below).

1.1. Models of Io's interior heating

Io's shape, density, moment of inertia and gravity are consistent with a fluid body that has differentiated into a metallic core and silicate mantle (Anderson et al., 2001), with a high degree of tidal heating making vigorous mantle convection very likely (Tackley, 2001). Advection of melt also plays a role (Moore, 2001) in the form of heat pipes into and through the lithosphere. The spatial distribution of interior heating depends strongly on the distribution of viscosity (Segatz et al., 1988; Tobie et al., 2005). The location of tidal heating and the resulting physical state of the interior leads to complex feedbacks from the associated temperature and melt distributions.

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In representative Maxwell viscoelastic models the radially integrated tidal heat production end members yield enhanced polar heat flow in the deep-mantle case and enhanced heat flow at lower latitudes and especially at sub- and anti-jovian regions in the aesthenospheric case (Ross et al., 1990; Segatz et al., 1988) (Fig. 1). The latter framework is supported by the presence of an induced magnetic field suggestive of a global magma ocean (Khurana et al., 2011).

The heating throughout a deep, partially molten mantle predicts hotter polar regions where the crust is thicker and more-voluminous, higher-temperature eruptions, with lower heat flux towards the equator where there are lower-temperature, less voluminous eruptions. Heat flow is high at the poles and low at the equator. The shallow aesthenospheric case predicts higher-temperature and larger eruptions at the equator, where the crust is thicker than at the poles, and lower-temperature, smaller eruptions at the poles. In this scenario, heat flow is high at the equator and low at the poles. The aesthenospheric heating model yields heat flow maxima at locations centered at 30° north and south of the equator at sub- and anti-jovian point longitudes (0°W and 180°W respectively), and secondary maxima at 90°W (centered on the equator at the central longitude of the leading hemisphere) and 270°W (centered on the equator at the central longitude of the trailing hemisphere).

Realistically, a mixture of deep and shallow heating is probably present, with values of 1/3 deep heating and 2/3 shallow heating used by other workers (Hamilton et al., 2013; Ross et al., 1990; Tackley et al., 2001). The results of mixing deep and shallow models on the resulting heat flow pattern are discussed below.

2. Io's global and volcanic heat flow

Models of global heat flow have to account for all of Io's thermal emission. Io's total global heat flow is estimated to be $1.06 \pm 0.12 \times 10^{14}$ W (Matson et al., 1981; Veeder et al., 1994, 2012). This global heat flow results in a very high average heat flow of 2.529 ± 0.265 W/m^2, especially when compared to Earth's global mean heat flow 0.087 W/m^2 (Pollack et al., 1993) and the Moon's $\approx$0.01–0.03 W/m^2 (Langseth et al., 1972; Warren and Rasmussen, 1987). Like the Earth and unlike the Moon, Io's local heat flow is widely variable depending on the proximity to ongoing and recent volcanic activity.

We have examined the estimated average thermal emission from 250 individual volcanic centers and eruption events to produce a global snapshot of Io's surface heat flow due to "hot spots" during the *Galileo* epoch (1996–2001) (Veeder et al., 2009, 2011, 2012, 2015). These thermal emission data are included in the Supplementary Material for this paper. The methods for calculating

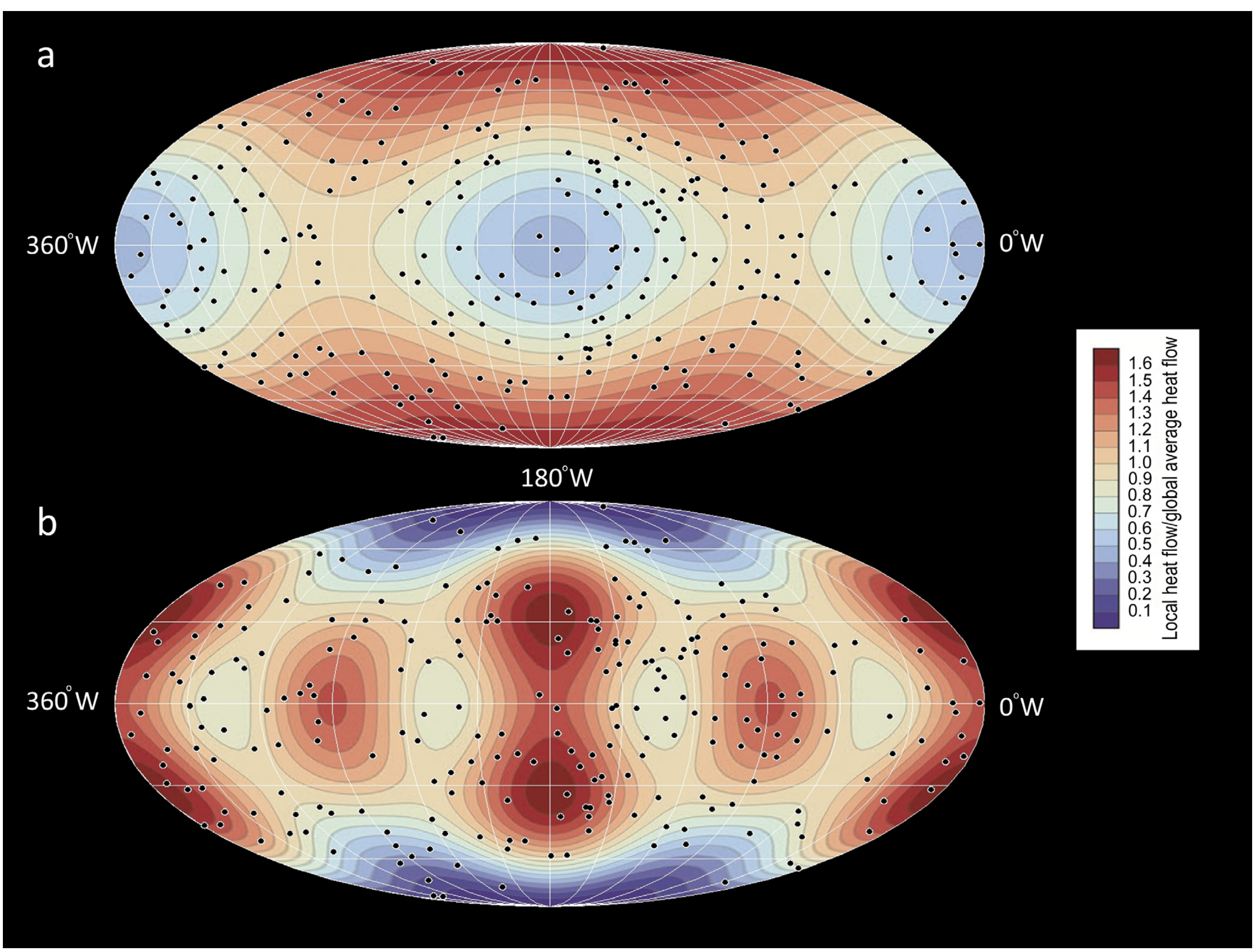

Fig. 1. Model tidal heating of Io. Mollweide projections of the end-members for expected heat flow from (a) deep mantle heating that results in most heat flow at the poles; and (b) shallow aesthenospheric heating with primary maxima at sub-jovian and anti-jovian longitudes (0°W and 180°W), secondary maxima at 270°W and 90°W and minima at the poles (after Hamilton et al., 2013). Individual thermal sources (see Veeder et al., 2015) are also shown as small black circles. Outburst eruptions are not included. North is up.