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Io: Heat flow from dark volcanic fields

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ABSTRACT

Dark flow fields on the jovian satellite Io are evidence of current or recent volcanic activity. We have examined the darkest volcanic fields and quantified their thermal emission in order to assess their contribution to Io's total heat flow. Loki Patera, the largest single source of heat flow on Io, is a convenient point of reference. We find that dark volcanic fields are more common in the hemisphere opposite Loki Patera and this large scale concentration is manifested as a maximum in the longitudinal distribution (near ∼200 °W), consistent with USGS global geologic mapping results. In spite of their relatively cool temperatures, dark volcanic fields contribute almost as much to Io's heat flow as Loki Patera itself because of their larger areal extent. As a group, dark volcanic fields provide an asymmetric component of ∼5% of Io's global heat flow or $\sim 5 \times 10^{12}$ W.

1. Introduction

Io is the most volcanically active body in the Solar System (Smith et al., 1979a,b; Morabito et al., 1979; Hanel et al., 1979). This activity is powered by strong tidal interactions (Peale et al., 1979; Yoder, 1979; Yoder and Peale, 1981; Segatz et al., 1988; Moore et al., 2007). Io's heat flow, which is more than predicted by tidal dissipation models, produces observed thermal infrared emission in excess of the re-radiation of absorbed solar insolation (Matson et al., 1981; Sinton, 1981; O'Reilly and Davies, 1981; Pearl and Sinton, 1982; Sinton and Kaminski, 1988; Stevenson and McNamara, 1988; Spencer et al., 1990, 2000; Veeder et al., 1994; Rathbun et al., 2004). Surface manifestations of the volcanic activity on Io include paterae, flows and plume deposits as well as fumaroles and molten lava (Schaber, 1982; Strom and Schneider, 1982; McEwen et al., 1998b; Geissler et al., 1999, 2004; Keszthelyi et al., 2001; Leone et al., 2008; see also general Io overviews by Nash et al. (1986), Spencer and Schneider (1996), Davies (2001, 2007), Geissler (2003), McEwen et al. (2004), Lopes and Williams (2005), and Perry et al. (2007)). The global distributions of volcanic centers and mountains on Io discussed by Carr et al. (1998) and Lopes-Gautier et al. (1999) have since been shown to be bimodal and anti-correlated (McKinnon et al., 2001; Radebaugh et al., 2001; Schenk et al., 2001; Kirchoff and McKinnon, 2005, 2009; Radebaugh, 2005). On regional and smaller scales, Io's paterae may have complex interfaces with mountains (e.g., Jaeger et al., 2003; Radebaugh et al., 2004; Turtle et al., 2001, 2007). In general, dark volcanic flows cover about 3% of Io's surface (McEwen et al., 1985; Geissler et al., 1999; Schenk et al., 2001; Zhang et al., 2002; Williams et al., 2008).

In previous work, qualitative analysis of Io's heat flow has been dominated by paterae, mostly because of the huge thermal emission from Loki Patera. In order to understand the role played by different types of volcanic activity (and possibly different supply mechanisms) in removing heat from Io's interior, we are quantitatively examining heat flow by eruption mode. In this paper we study dark flow fields (excluding plume deposits). These low albedo fields are currently or recently active, thus providing a snapshot of thermal output from this class.

Io's thermal emission is dominated by Loki Patera, Io's largest patera. The dark material within Loki Patera radiates between 5% and 15% (averaging $\sim 6 \times 10^{12}$ W) of Io's total heat flow ($\sim 1 \times 10^{14}$ W) from less than ∼0.1% ($\sim 2 \times 10^{4}$ km^2) of Io's total surface area ($\sim 4 \times 10^{7}$ km^2) (e.g., Pearl and Sinton, 1982; Veeder et al., 1994; Rathbun et al., 2004; Rathbun and Spencer, 2006; Matson et al., 2006). Until now, however, no comparison has been made between thermal emission from Loki Patera and that from the dark flow field to the NE of the patera. This flow field, nearly 200 km long, is a major volcanic feature in its own right, and was the source of two plumes observed by the *Voyager* spacecraft (e.g., Smith et al., 1979a,b; Strom and Schneider, 1982; McEwen et al., 1985). Moreover, several other of Io's volcanic fields are much larger than Loki Patera. We examine thermal emission from all of these dark flow fields and compare this with thermal emission from Loki Patera as a point of reference.

Regarding other dark flow fields, surface changes and variations in radiative power output have been observed at Amirani and Prometheus (e.g., Keszthelyi et al., 2001; Davies, 2003; Lopes et al., 2004; Davies et al., 2006b). In general, dark flows are

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expected to have been recently active. Many flow fields include hot spots that may be persistent as well as variable in some cases (e.g., Lopes-Gautier et al., 1999; Ennis and Davies, 2005). Such volcanic flows display a wide range of temperatures as they erupt and cool (Crisp and Baloga, 1990; Davies, 1996; Davies et al., 2000, 2005). Their average effective temperatures are less than is typical for paterae (e.g., Loki Patera), but their combined areas are much larger. Thus, dark fields can make a significant contribution to the heat flow of Io.

Io radiates most of its power in the far infrared. Volcanic fields are expected to emit a larger fraction of their power at longer wavelengths than warmer paterae. Although thermal infrared maps of Io have limited coverage, dark volcanic features (including fluctus, paterae and "eruptive centers" as defined by the USGS) are well correlated with hot spots (see previous references). Active volcanic features on Io known from *Voyager* InfraRed Interferometric Spectrometer (IRIS), *Galileo* Solid State Imaging (SSI), Near Infrared Mapping Spectrometer (NIMS), and Photopolarimeter–Radiometer (PPR) data as well as from ground-based observations have been discussed and classified by Lopes et al. (2004, 2007), Rathbun et al. (2005), Davies and Keszthelyi (2005), Davies et al. (2007) and Davies (2007).

Since thermal infrared observational coverage of volcanic fields on Io is incomplete (both spatially and temporally), we estimate their total heat flow contribution by using additional information from the following sources: (1) *Voyager* and *Galileo* images (McEwen et al., 1998b, 2000; Schenk et al., 2004; Turtle et al., 2004, 2007). (2) *Galileo* maps (Crown et al., 1992; Becker and Geissler, 2005; Williams et al., 2002, 2004, 2005a,b, 2007, 2008; Davies, 2007). (3) *Galileo* near infrared observations (Davies et al., 1997, 2000, 2005; Lopes-Gautier et al., 1997, 1999, 2000; Smythe et al., 1999, 2002; Lopes et al., 2001, 2004; Davies, 2003; Ennis and Davies, 2005). (4) Eclipse observations (McEwen et al., 1997, 1998a,b; Keszthelyi et al., 2001; Marchis et al., 2002, 2005; Macintosh et al., 2003; Radebaugh et al., 2003; de Pater et al., 2004). (5) *New Horizons* observations (Spencer et al., 2007). While many small flows occur on the floors of paterae, we regard these as parts of their associated paterae and do not address them here. This paper is focused on larger dark fields not confined within such paterae.

2. Dark volcanic field distributions

2.1. Numerical surface distribution

We have examined 28 of Io's largest dark volcanic fields on global and regional images and maps (see Fig. 1). The name, latitude, longitude, notes and references for each of these dark volcanic fields on Io are listed in Table 1. Locations of flows and paterae may refer to either their centers as seen in images or the positions of their associated hot spots (see especially, Radebaugh et al., 2001; Radebaugh, 2005; Lopes et al., 2004, 2007; Davies, 2007). Further information on the visual context of flows and paterae on Io is found in Crown et al. (1992), Becker and Geissler (2005), McEwen et al. (2004), and Williams et al. (2002, 2004, 2005a,b, 2007, 2008). The fluctus and patera nomenclature used in this paper is based on reports and maps of the USGS Astrogeology Research Program.

The most complex volcanic field considered is Lei-Kung Fluctus which displays a range of albedos. Here we emphasize its darker regions. This results in five separate entries in the tables which are all part of its very large field. Since this paper is focused on large dark volcanic fields on Io, the following types of features have been excluded: (1) Light colored flows; e.g., Donar, Fjorgynn, Lei-zi, Maasaw, Mbali, Ra, Tsui Goab, Tung Yo and Uta (Crown et al., 1992; Williams et al., 2008). (2) Low contrast flows including some that lie near *Galileo* infrared sources; e.g., Boosaule, Kanehekili, Lerna, Seth, and Wayland (Lopes et al., 2004; Rathbun et al., 2004). (3) Confined activity within Tvashtar Paterae (McEwen et al., 2000, 2004; Lopes et al., 2004; Turtle et al., 2004; Milazzo et al., 2005; Spencer et al., 2007). (4) Transient activity at Thor (Lopes et al., 2004; Turtle et al., 2004; Williams et al., 2005b). (5) Pillan. This was the site of a large eruption in 1997 that emplaced 10 m thick lava flows over an area of 5600 km^2 (Davies et al., 2001; Keszthelyi et al., 2001; Williams et al., 2001). Over 56 km^3 of material was erupted near and flowed into Pillan Patera itself (Davies et al., 2006a). Despite the magnitude of the thermal emission from this eruption at its height (Davies et al., 2001), the overall contribution to Io's thermal emission from Pillan over a long period of time (decades) is very small (Davies, 2007) and is therefore not included in this analysis.

The number of large volcanic flow fields on Io is smaller than the known populations of paterae and hot spots. Mapped volcanic flows on Io range over all latitudes. On the other hand, we find that dark volcanic fields have a distribution in longitude which is quite distinct from that of either paterae considered by themselves or volcanic centers considered altogether. On Io, paterae and mountains both have bimodal spatial distributions that are anti-correlated (McKinnon et al., 2001; Radebaugh et al., 2001; Schenk et al., 2001; Kirchoff and McKinnon, 2005, 2009; Radebaugh, 2005). The numeric density of large dark fields is concentrated near $\sim 200°$W when weighted by area (see Fig. 2). This distribution has also been confirmed by new global geologic mapping (D.A. Williams, pers. comm., 2009). This location correlates with only one of the high density concentrations for volcanic centers and paterae; and likewise, with only one of the regions of low density in the spatial distribution of mountains.

2.2. Model areas

The dark flow areas of our selected flow fields are determined, for the most part, from the USGS Io Global Mosaic (Becker and Geissler, 2005). We use a version of the mosaic that has a pixel scale of 0.837 km $pixel^{-1}$. For each flow field the global mosaic is re-projected from a simple cylindrical projection to an orthographic projection with the center of the flow field at the center of the image. This minimizes distortion of the flow image. Each flow field image is then extracted from the re-projected mosaic, converted to grayscale (not shown), and rescaled so that the pixel scale is 0.558 km $pixel^{-1}$. The color images are shown in Fig. 3.

The next step in the process is to identify the areas of each flow field that are considered 'dark'. An image processing program written in Interactive Display Language (IDL) is used iteratively to identify a cut-off brightness level (the threshold) to isolate these dark flow areas. This process, which includes comparison with other views and maps, is necessarily subjective. We acknowledge that the USGS construction of mosaic images involves airbrushing and adjustment for apparent albedo and phase angle effects as well as geometric splicing near overlapping boundaries (Becker and Geissler, 2005; Williams et al., 2009). This means that the threshold varies from flow field to flow field, from a low of 85 at Zamama, to a high of 160 at Nina (E) (ID 10). Where necessary, non-flow dark areas (such as nearby dark paterae) are erased.

The IDL program counts the number of remaining (selected) dark pixels below the threshold and multiplies the total by the pixel area. This process is intended to emphasize each contiguous dark flow and is complementary to the global mapping of geologic units as in Williams et al. (2009). This process also differs from the method of counting all threshold pixels within a frame utilized by McEwen et al. (1985). The adopted areas of dark material within each volcanic field are shown in Table 2 and as black on white in Fig. 4 (with the same scale as Fig. 3).