Io: Volcanic Advection and Heat Flow

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Io’s hot spots
Observations
Modes of volcanic activity
Quantifying thermal emission
Derivation of erupted volumes
Heat flow analysis
Questions
Volcanism on Io

- The most extreme example of tidal heating in the Solar System
- Powerful, highly voluminous eruptions
- Resurfacing has erased all impact craters
- Lithosphere is *cold*
- Heat pipe volcanism (Moore, 2014)
- Faults can be exploited (e.g., Leone et al., 2009)
What is the composition of silicate lavas on Io?

Io’s volcanism is dominated by low-viscosity, quite fluid lavas.

- **Basalt** erupts at ~1150 °C (~1440 K)
- **Komatiite** erupts at ~1577 °C (~1850 K)

The hotter the lava $\rightarrow$ more interior heating $\rightarrow$ a more liquid source area.
Voyager and Galileo data
Io from Earth: Keck AO data (4.7 µm)

Marchis et al. (2001) Icarus
Io volcanoes ranked by thermal emission

242 sources account for ~54% of Io’s heat flow (~70% from paterae)
With outbursts = ~57% of Io’s heat flow

Veeder et al. (2015) Icarus
Galileo NIMS and SSI observe volcanism on Io

Pillan, 1997

NIMS

Davies et al., 2001

Tvashtar Paterae, Feb 2000

Keszthelyi et al., 2001

Loki Patera surface temperature map from NIMS data

Pillan flows at 9 m/pixel

Silverman et al., 2001

Loki Patera surface temperature map from NIMS data

Williams et al., 2001

Prometheus – tube-fed lava flows

Surface flows

Breakouts/skylights?

Main vent

NIMS: 24INPROMTH91A  11 Oct 1999
Average spatial resolution: 1.4 km/pixel

Leone et al. (2009) *Icarus*
Paterae – ubiquitous on Io – source of most endogenic heat – catalogued by Radebaugh et al., 2001

Veeder et al. (2011)
Possible patera formation mechanism – Keszthelyi et al., 2004

Figure from Davies, 2007, *Volcanism on Io*, p244.
Flow fields on Io range in size from ~600 km\(^2\) to >2.5 x 10\(^5\) km\(^2\)
Volcanism is dominated by high-temperature, low viscosity silicates

Activity also driven by interactions with exsolving primary volatiles and with lithospheric volatiles during ascent ($S, SO_2$) and on the surface

Many active paterae (e.g., Radebaugh et al., 2002; Lopes et al., 2004)

Extensive lava flow fields (e.g., see Veeder et al., 2009)

Active, overturning lava lakes (Janus Patera, Pele – e.g., Davies et al., 2001)

and....
At least one quiescently overturning lava lake (or lava “sea”) – Loki Patera (e.g., Rathbun et al., 2002; Davies, 2003; Matson et al., 2006; Rathbun and Spencer, 2006; de Kleer et al., 2017).

- Powerful, dike-fed lava fountain episodes feeding voluminous flows (likely cause of “outbursts”) (See Davies, 1996)

- Smaller and more frequent fountain events (de Kleer and de Pater, 2016a,b)

- Secondary S, SO₂ volcanism (see Prometheus plume papers: e.g., Kieffer et al., 2000)

- Transient explosive activity (Davies et al., 2018, GRL)
Amirani eruption rate (TADR) estimation

- 620 km² new flows
- 23 breakouts
- 134 days
- TADR = 60-600 m³/s

Keszthelyi et al., 2001

Flow thickness in this case is not known

Williams et al. (2001) measured post-eruption flow thickness at Pillan = ~10 m

Davies et al. (2000) and Davies (2003) used NIMS data to estimate eruption volumetric rates
Calculation of effusion rate (2)

- From thermal emission: best with multi-wavelength infrared data
  - *Galileo* NIMS data (0.7 to 5.2 μm)
  - AO data (~2 to ~5 μm)

- NIMS sensitive down to surfaces at ~200 K

- Models of thermal emission – fit combination of black body curves to the data
  
  $1T$, $2T$ fits (Davies *et al.*, 1997, 2001, etc., etc.)

Multiple temperature component models (Carr, 1986; Davies, 1996; Howell, 1997)

*Davies, 1996 - Derives areal coverage rate – variants utilise variable effusion rate, lava crust crack fraction, separate vent and flow units*
Cooling curves for lavas on Io

- Komatiite (1850 K)
- Basalt (1470 K)
- Sulphur (393 K)

Davies et al., 2005
Calculation of effusion rate \( q_{F(NIMS)} \), m\(^3\)/s

- Using NIMS data - Davies et al. (2000)
- Calculate \( F_{rad} \)
- Determine eruption style (flows, lake, other)
- If flows, calculate \( F_{cond} = 20\% F_{rad} \); Johnson et al., 1995; Davies, 2003); \( F_{rad} = F_{rad} \)

\[
q_{F(NIMS)} = \frac{F_{tot}}{\rho_{lava} (L + c_p [T_{erupt} - T_{NIMS}])}
\]

\( \rho_{lava} \) = lava density
\( L \) = latent heat of solidification
\( c_p \) = specific heat capacity
\( T_{erupt} \) = lava eruption temperature
\( T_{NIMS} \) = minimum NIMS detection threshold (filled pixel = 180 K)
IFM – generation of integrated thermal emission spectrum

Active flow

\[ Q_{rad,(\lambda),i} = \sum_{i=1}^{n} \frac{c_1 \varepsilon}{\lambda^5} \left( (1 - f) \left( \frac{A_i}{e^{c_2/\lambda T_{crust}}} - 1 \right) \right) + \left( f \left( \frac{A_{i,crack}}{e^{c_2/\lambda T_{eruption}}} - 1 \right) \right) \]

Active vent

\[ Q_{rad,(\lambda),i} = \sum_{i=1}^{n} \frac{c_1 \varepsilon}{\lambda^5} \left( \frac{A_{i,crack}}{e^{c_2/\lambda T_{crust}}} - 1 \right) \]

Cool crust

Crack fraction

Lava fountains; Roiling “cauldron”

After Davies (1996, 2007)
Temp/area model fits to NIMS data

IFM dual-component fit to Pillan outburst
Davies et al., 2001, *JGR*

2-T, 2-A fit to Prometheus data, G1, June 1996
Davies and Ennis, 2011, *Icarus*

Interpretation – lava fountains feeding expanding flows

Interpretation – active flows with insulated crusts
Temp/area model fits to NIMS data

IFM dual-component fit to **Pele** NIMS data, 1998
Davies et al., 2001, *JGR*

**Interpretation** – active, overturning lava lake –
Spectral signature similar to terrestrial lava lakes

Variable spectra of **Loki Patera** in NIMS data – 2T fits
Matson et al., 2006, *JGR*; Davies et al., 2010, *JVGR*

**Interpretation** – periodic, quiescently overturning lava lake
e.g., Rathbun et al., 2002; Davies, 2003; de Kleer et al., 2017
Effusion rate variability

Effusion (instantaneous) volumetric rate estimated by balancing observed thermal emission from active flows against latent and sensible heat release of a volume of lava (see Davies, 2007; Harris, 2013, et al.).

Davies and Ennis (2011)
AO-detected outbursts – Rarog and Heno Paterae

Rarog P. 15 Aug.
Rarog P. 20 Aug.
Rarog P. 22 Aug.
Heno P. 15 Aug.
Heno P. 20 Aug.
Heno P. 22 Aug.

[Graph showing spectral radiance versus wavelength for different dates and locations, with labels for Rarog and Heno Paterae]

de Pater et al. (2014a) Icarus
AO-detected outbursts – Rarog and Heno Paterae

- Effusion rate
- Eruption rate

<table>
<thead>
<tr>
<th></th>
<th>Duration (days)</th>
<th>Area covered (km²)</th>
<th>Volume erupted* (km²)</th>
<th>Peak $Q_f$ (m²)</th>
<th>$Q_e$ (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heno Patera</td>
<td>7</td>
<td>1300</td>
<td>13</td>
<td>$10^5$</td>
<td>$2 \times 10^4$</td>
</tr>
<tr>
<td>Rarog Patera</td>
<td>6</td>
<td>540</td>
<td>5</td>
<td>$5 \times 10^4$</td>
<td>$10^4$</td>
</tr>
</tbody>
</table>

*assuming Pillan-like 10-m thick flows
Io’s eruptions take place on scales that dwarf contemporary eruptions on Earth.

20 years of activity at Prometheus and Kilauea

Effusion rate comparisons – contemporary eruptions

- Earth
- Io

- Pahoehoe flows
- Lava lake
- Open channel flows
- Pillan
- No terrestrial equivalent

Region 1990

Mauna Loa

Pele
Io: volcanic IR thermal emission

Davies et al. (2017) JVGR
5 µm = 2 µm

2-µm radiant flux, GW µm⁻¹

1.0E-03 1.0E-02 1.0E-01 1.0E+00 1.0E+01 1.0E+02 1.0E+03 1.0E+04 1.0E+05

1.0E-03 1.0E-02 1.0E-01 1.0E+00 1.0E+01 1.0E+02 1.0E+03 1.0E+04 1.0E+05

Loki Patera: “Quiescent” lava lake

Old flows and inactive lakes

Flows with insulating crusts

Active lava lakes

Small fountain event?

After Davies, Keszthelyi and Harris (2010)
After Davies, Keszthelyi and Harris (2010) \textit{JVGR}
Style of volcanic activity and derivation of $T_{erupt}$
Post-Galileo view of Io’s volcanism

Davies (2007) Volcanism on Io, p289
Heat Flow – follow-up
Heat flow from Io’s volcanoes: 250 sources

Io’s global heat flow: $1.05 \pm 0.1 \times 10^{14}$ W (Veeder et al., 1994, 2012)

Data from Veeder et al. (2015)

Unaccounted for = 46%

"Hot spot" total = 54%
Tidal heating and surface heat flow

End member cases  (Segatz et al., 1988; Ross et al., 1990)

Realistically, a mixture of deep and shallow heating is probably required e.g., Tackley et al., 2001; see Hamilton et al. (2013) for 1/3 deep. 2/3 shallow case
Heat flow map (centre lon. 180° W)
Io’s average heat flow

Average active area volcanic heat flow (2% of Io) \( \approx 68 \text{ W/m}^2 \)

What of the 46% “unaccounted” heat flow?

Spread evenly across Io, this equals \( 0.98 \pm 0.05 \text{ W/m}^2 \)
- Earth = 0.07 \text{ W/m}^2
- Moon = 0.03 \text{ W/m}^2

This value of 0.98 \text{ W/m}^2 is used to set the base heat flow for the heat flow map
Veeder et al. (2012, 2015) Io volcanic heat flow distribution

Preponderance of thermal emission towards lower latitudes

Slightly more thermal emission in N hemisphere (not including Loki Patera)

Favours aesthenospheric tidal heating
Distribution of volcanic thermal emission as measured by Veeder et al., 2012, 2015.

Thermal emission from large lava fields – single peak at ~220° W.

Dark paterae in a bimodal distribution dominate thermal emission

Total thermal emission peaks at ~315° W and ~105° W.

This is a shift eastwards from that expected from aethenospheric heating

Hamilton et al. (2013) found the same shift from studying volcanic features; partly mitigated by lateral movement of melt (Tyler et al., 2015)

Minimum at ~200° W is real – area is well imaged

Minimum at 345° W to 45° may be real as imaging is low resolution
The mismatch between the 2013–2015 hot spot numbers and the Galileo power measurements (blue and purple lines) from 120 °W to 150 °W may be due to the particularly high concentration of low-intensity hot spots in this region. de Kleer and de Pater (2016) Icarus, 260, 405-414.
Ground-based detections of medium to large volcano thermal emission plotted on the deep-mantle tidal heating model.

Shallow tidal heating model with a partially-fluid interior, base image from Tyler et al. (2015).

Heat flow from Io’s volcanoes: 250 sources

Io’s global heat flow: $1.05 \pm 0.1 \times 10^{14}$ W (Veeder et al., 1994, 2012)

“Unaccounted” possibilities - (Veeder et al., 2012)

Old, cool flows not imaged by PPR

“Layer cake” lava flow stacks

Shallow intrusions, releasing heat slowly at the surface

Low-temperature surface activity ($S, SO_2$)

Very small thermal sources

Low T volatile movement (e.g., “stealth” plumes)

Poorly imaged polar heat flow (see Matson et al., 2004)
Questions

- Can we be sure that the observed distribution of volcanism reflects the distribution and magnitude of tidal heating?

- What is the dominant composition of Io’s lavas, and does this change with location?

- Is volcanic activity tidally controlled at a local or regional level?

- What constraints on interior modelling can be met through remote sensing, both from the ground and from spacecraft?

- What of the “unaccounted for” heat flow? (e.g., low temperature S, SO$_2$ volcanism, not observed by *Galileo* – see Veeder et al., 2012, 2015)

- What causes the offset in heat flow?
  - no mix of deep and shallow heating can account for the offset
  - lateral melt movement is only partial solution
Data: Veeder et al. (2015) *Icarus* – Excel spreadsheet available in Supplementary Material