

Galileo at 30 - A Celebration

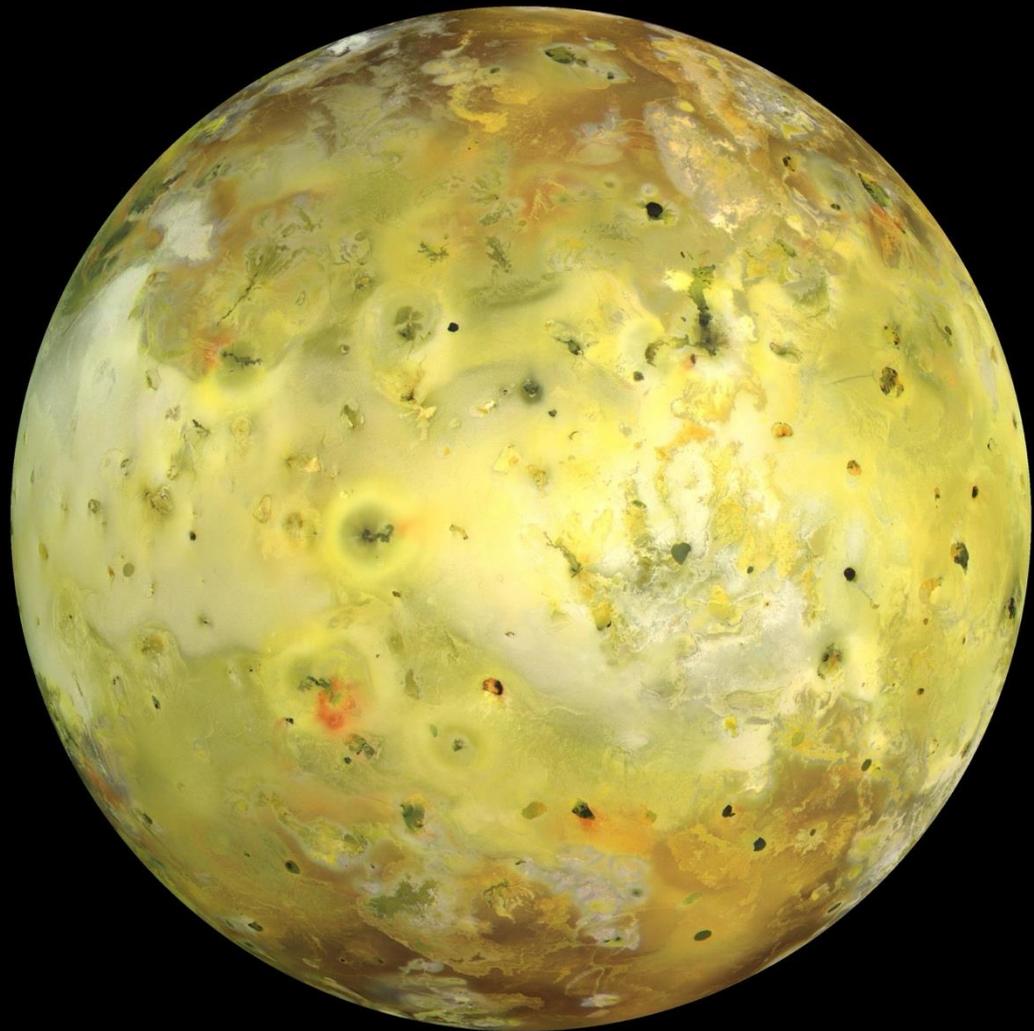
Io

Ashley Gerard Davies

Jet Propulsion Laboratory - California Institute of Technology

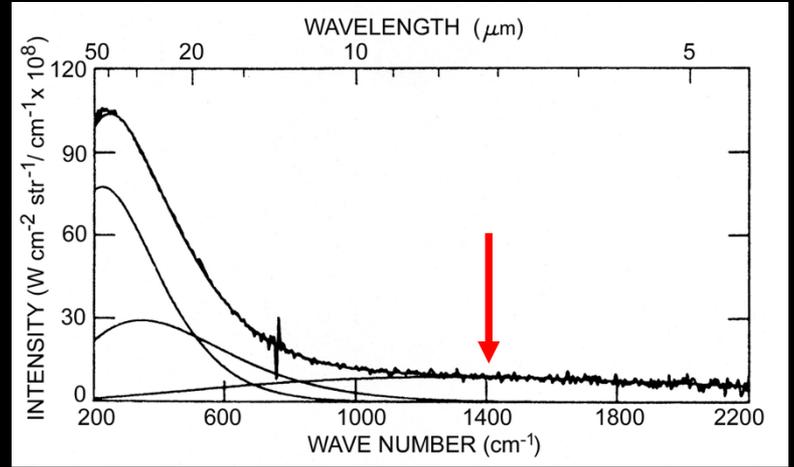
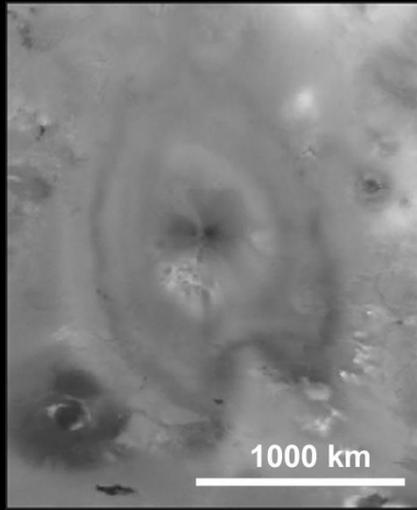
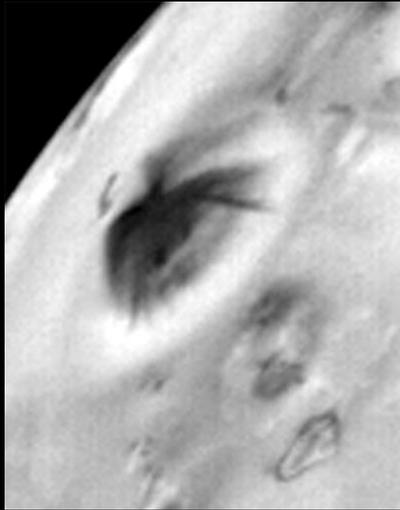
8 December 2025



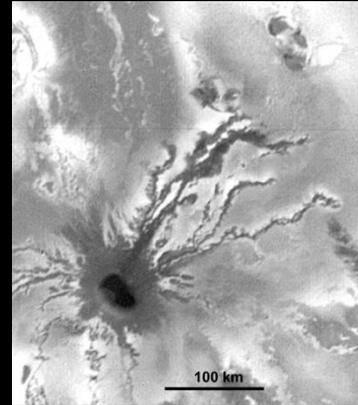
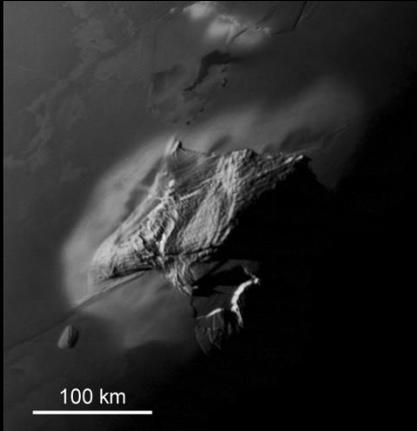


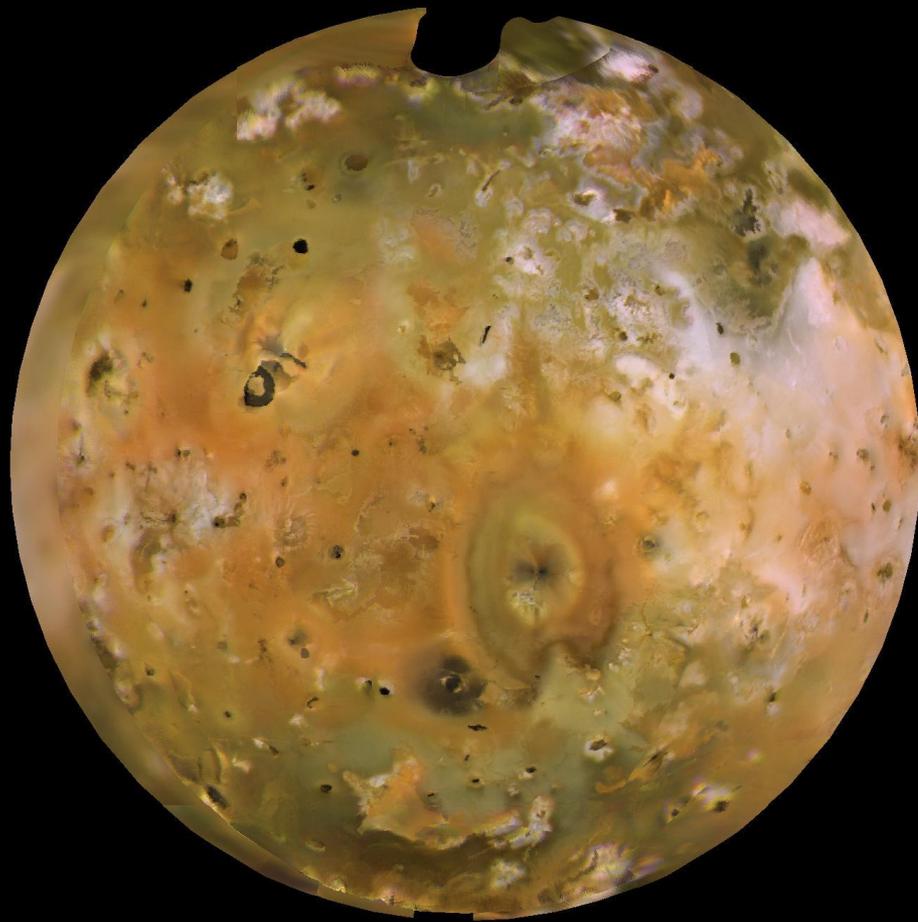
Volcanic plumes



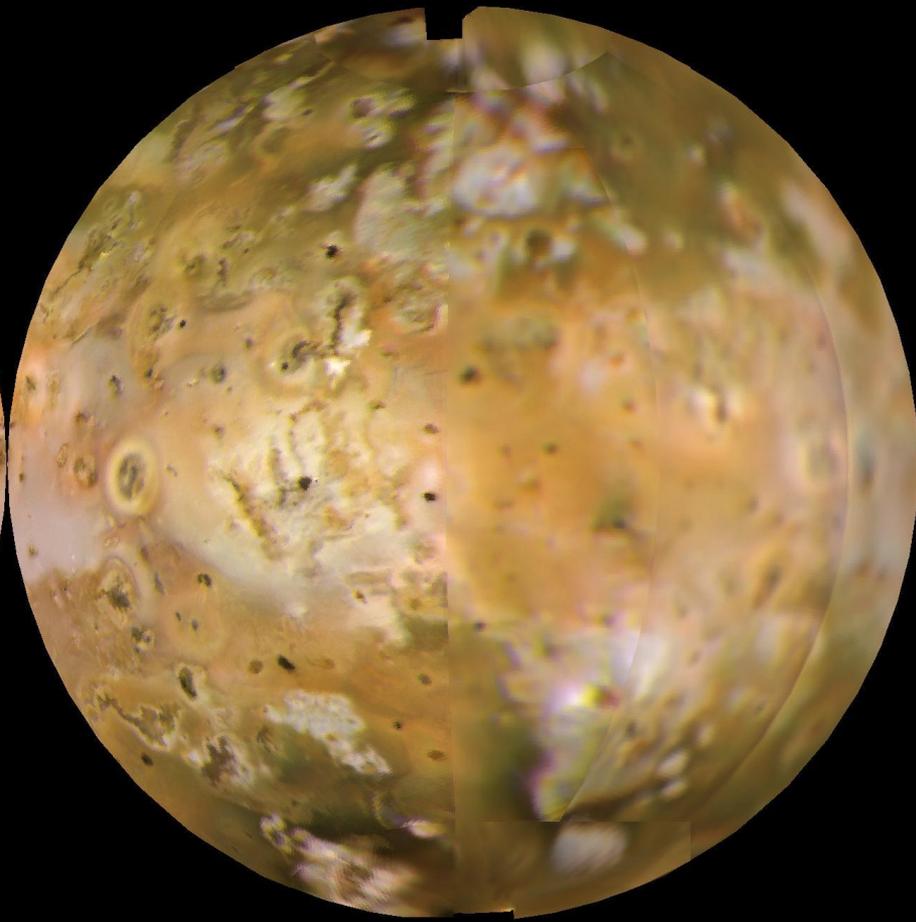


Pearl and Sinton, 1982

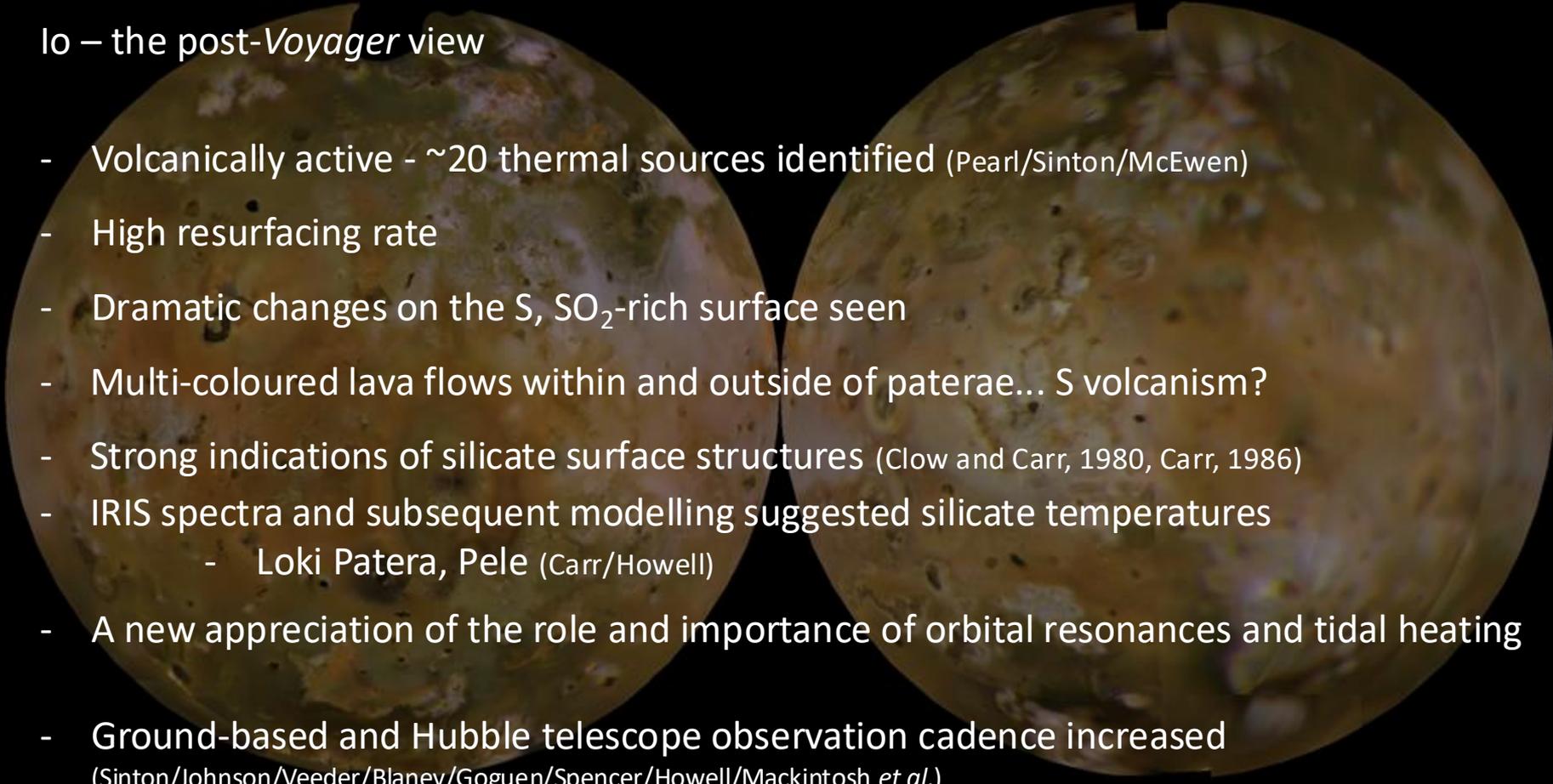




Trailing hemisphere



Leading hemisphere



Io – the post-*Voyager* view

- Volcanically active - ~20 thermal sources identified (Pearl/Sinton/McEwen)
- High resurfacing rate
- Dramatic changes on the S, SO₂-rich surface seen
- Multi-coloured lava flows within and outside of paterae... S volcanism?
- Strong indications of silicate surface structures (Clow and Carr, 1980, Carr, 1986)
- IRIS spectra and subsequent modelling suggested silicate temperatures
 - Loki Patera, Pele (Carr/Howell)
- A new appreciation of the role and importance of orbital resonances and tidal heating
- Ground-based and Hubble telescope observation cadence increased
(Sinton/Johnson/Veeder/Blaney/Goguen/Spencer/Howell/Mackintosh *et al.*)

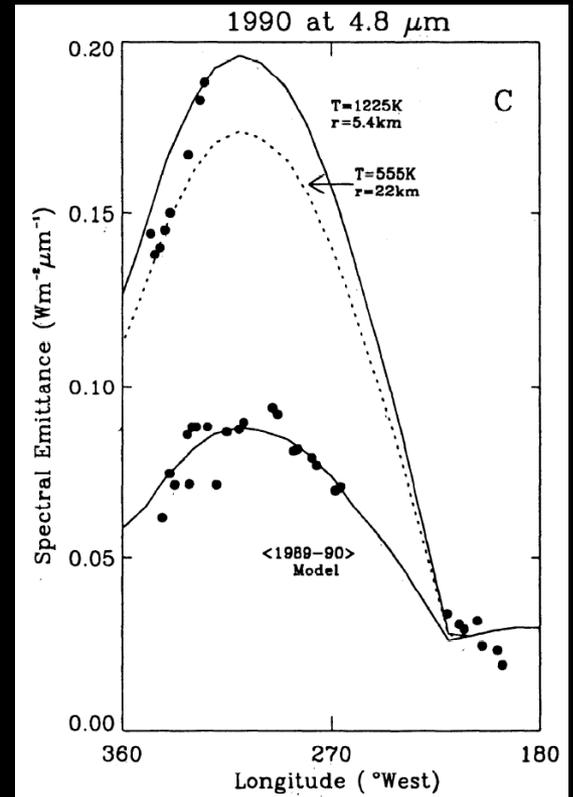
Io's heat flow from infrared radiometry: 1983-1993

Glenn J. Veeder, Dennis L. Matson, Torrence V. Johnson, Diana L. Blaney, and Jay D. Goguen

Jet Propulsion Laboratory, California Institute of Technology, Pasadena

Abstract. We report the following results from a decade of infrared radiometry of Io: (1) The average global heat flow is more than $\sim 2.5 \text{ W m}^{-2}$, (2) large warm ($\leq 200 \text{ K}$) volcanic regions dominate the global heat flow, (3) small high-temperature ($> 300 \text{ K}$) "hotspots" contribute little to the average heat flow, (4) thermal anomalies on the leading hemisphere contribute about half of the heat flow, (5) a substantial amount of heat is radiated during Io's night, (6) high-temperature ($\geq 600 \text{ K}$) "outbursts" occurred during $\sim 4\%$ of the nights we observed, (7) "Loki" is the brightest, persistent, infrared emission feature, and (8) some excess emission is always present at the longitude of Loki, but its intensity and other characteristics change between apparitions. Observations of Io at M ($4.8 \text{ }\mu\text{m}$), $8.7 \text{ }\mu\text{m}$

1986, 1990 Io Outbursts



Io's heat flow from infrared radiometry: 1983-1993

Glenn J. Veeder, Dennis L. Matson, Torrence V. Johnson, Diana L. Blaney, and Jay D. Goguen

ICARUS 113, 220–225 (1995)

Jet Propulsion Labora

Abstract. We report (1) The average global regions dominate the contribute little to the night, (6) high-temperature observed, (7) "Lok excess emission is a characteristics change

NOTE

Volcanic Eruptions on Io: Heat Flow, Resurfacing, and Lava Composition

DIANA L. BLANEY,* TORRENCE V. JOHNSON,* DENNIS L. MATSON,* AND GLENN J. VEEDER*

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Received July 5, 1994; revised September 13, 1994

We model an infrared outburst on Io as being due to a large, erupting lava flow which increased its area at a rate of $1.5 \times 10^5 \text{ m}^2 \text{ sec}^{-1}$ and cooled from 1225 to 555 K over the 2.583-hr period of observation. The inferred effusion rate of $3 \times 10^5 \text{ m}^3 \text{ sec}^{-1}$ for this eruption is very high, but is not unprecedented on the Earth.

Subsequently, other such outbursts have been reported (Sinton *et al.* 1983, Johnson *et al.* 1988, Howell and Sinton 1989, McEwen *et al.* 1989, Veeder *et al.* 1994). In this paper we consider the outbursts observed over the past 15 years and examine the implications for resurfacing rates and heat flow obtained from a well-observed eruption reported by Veeder *et al.* (1994).

Io's heat flow from infrared radiometry: 1983-1993

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ICARUS 124, 45-61 (1996)
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DIANA L. BLANEY,* TORRENCE V. J

*Jet Propulsion Laboratory, Califor
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We model an infrared outburst on Io as being due erupting lava flow which increased its area at a rate of $m^2 sec^{-1}$ and cooled from 1225 to 555 K over the 2.58 of observation. The inferred effusion rate of $3 \times 10^5 m^3$ in this eruption is very high, but is not unprecedented on

Io's Volcanism: Thermo-Physical Models of Silicate Lava Compared with Observations of Thermal Emission

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Received February 26, 1996; revised May 1, 1996

Analyses of thermal infrared outbursts from the jovian satellite Io indicate that at least some of these volcanic events are due to silicate lava. Analysis of the January 9, 1990 outburst indicates that this was an active eruption consisting of a large lava flow (with mass eruption rate of order $10^5 m^3 sec^{-1}$) and a sustained area at silicate liquidus temperatures. This is interpreted as a series of fire fountains along a rift zone. A possible alternative scenario is that of an overflowing lava lake with extensive fire fountaining. The January 9, 1990 event is unique

posed to sulfur volcanism. With these new data available, it is now necessary to consider the fluid and thermodynamic behavior of lava eruption and emplacement in order to explain the temporal evolution of these outbursts, and reevaluate the role active volcanism plays in the Io thermal budget.

The largest class of outbursts on Io are characterized by a large increase in the $4.8 \mu m$ emission over a short period of time (i.e., hours to days). The first report of such an event was the pre-Voyager $5 \mu m$ enhancement reported

NIMS GUIDE TO THE J0 ORBIT

Original: December 1995

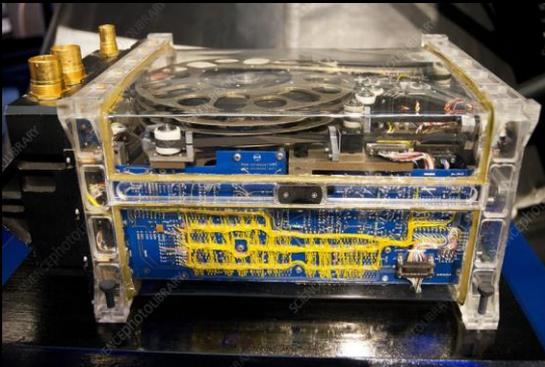
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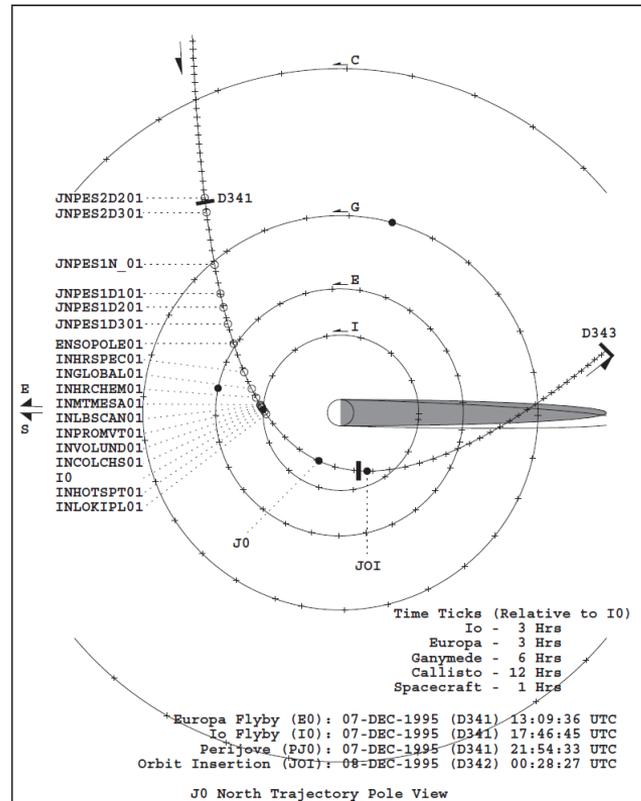
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Introduction

This J0 orbit was the first flyby of Jupiter in Galileo's Tour of the Jovian system. Unfortunately, due to problems with the spacecraft's tape recorder, no NIMS data were recorded during J0. This was the only flyby of Io in Galileo's main mission. Close flybys of Io are planned for the GEM orbits I24 and I25.



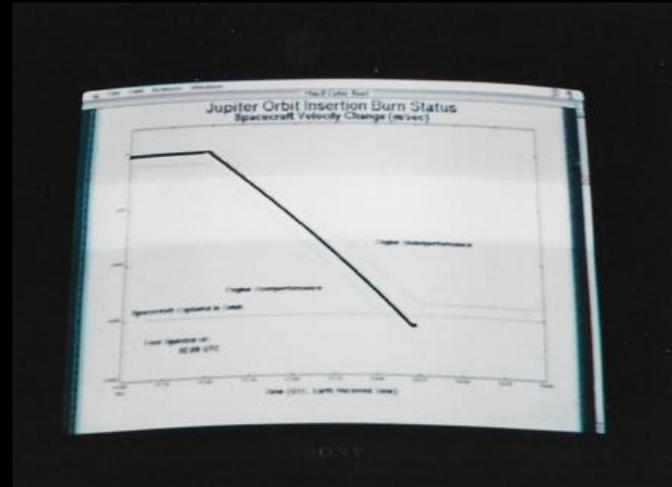
NIMS J0 OBSERVATIONS



NIMS - FEL - 05/26/98

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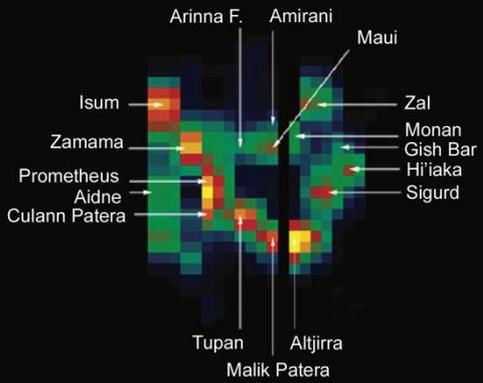
JOI – 7 December 1995



Io observations - *Galileo* Prime Mission

First 11 orbits: June 1996 (G1) - November 1997 (E11)

- global observations, at relatively low spatial resolutions
~5-20 km/pixel (SSI); 122 to 725 km/pixel (NIMS)
- allowed monitoring of Io's volcanism and surface changes (Keszthelyi/McEwen)
- hot spot identification and modelling of NIMS hot spot spectra (Lopes/Davies)
- SO₂ mapping (Carlson/Doute)
- comparison with *Voyager* and Hubble data (McEwen/Spencer)



G1INNSPEC01, 28 June 1996. NIMS, 4.8 μm . Davies (2007) after Lopes *et al.* (1997)

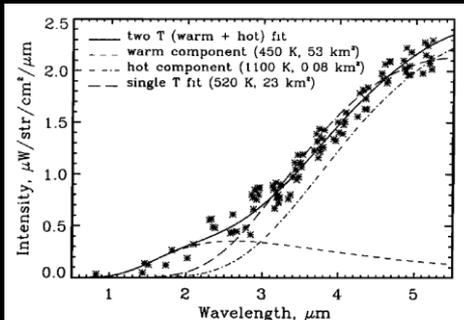
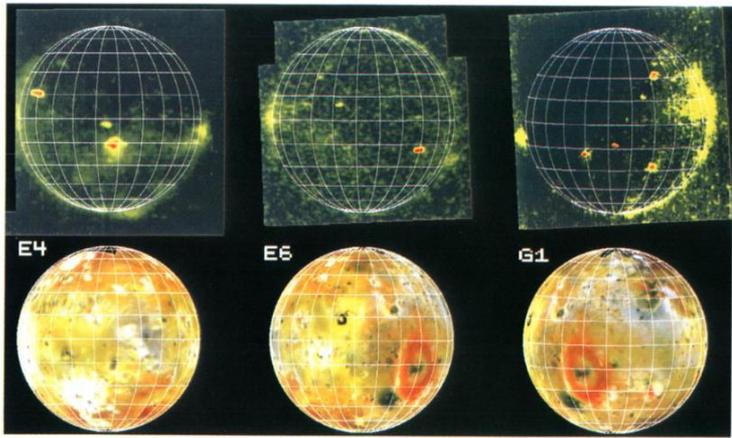


Figure 2. Single (long-dash) and two-temperature (solid) fits to the S. Volund NIMS data (stars). The standard deviation of the fit of the two temperature model (1100 K, 0.08 km², dot-dash line; and 450 K, 53 km², short-dash line) is 40% less than that obtained from the single temperature (520 K, 23 km²) fit.

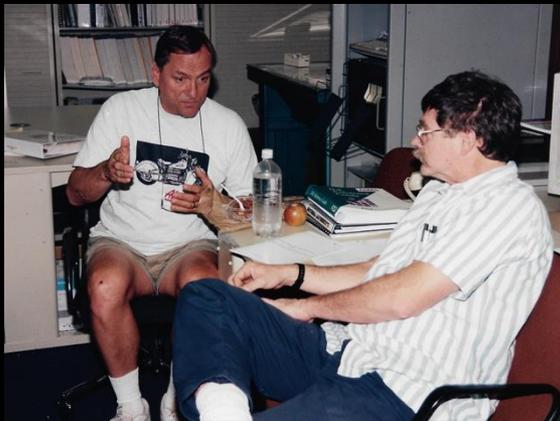
Davies *et al.* (1997) GRL

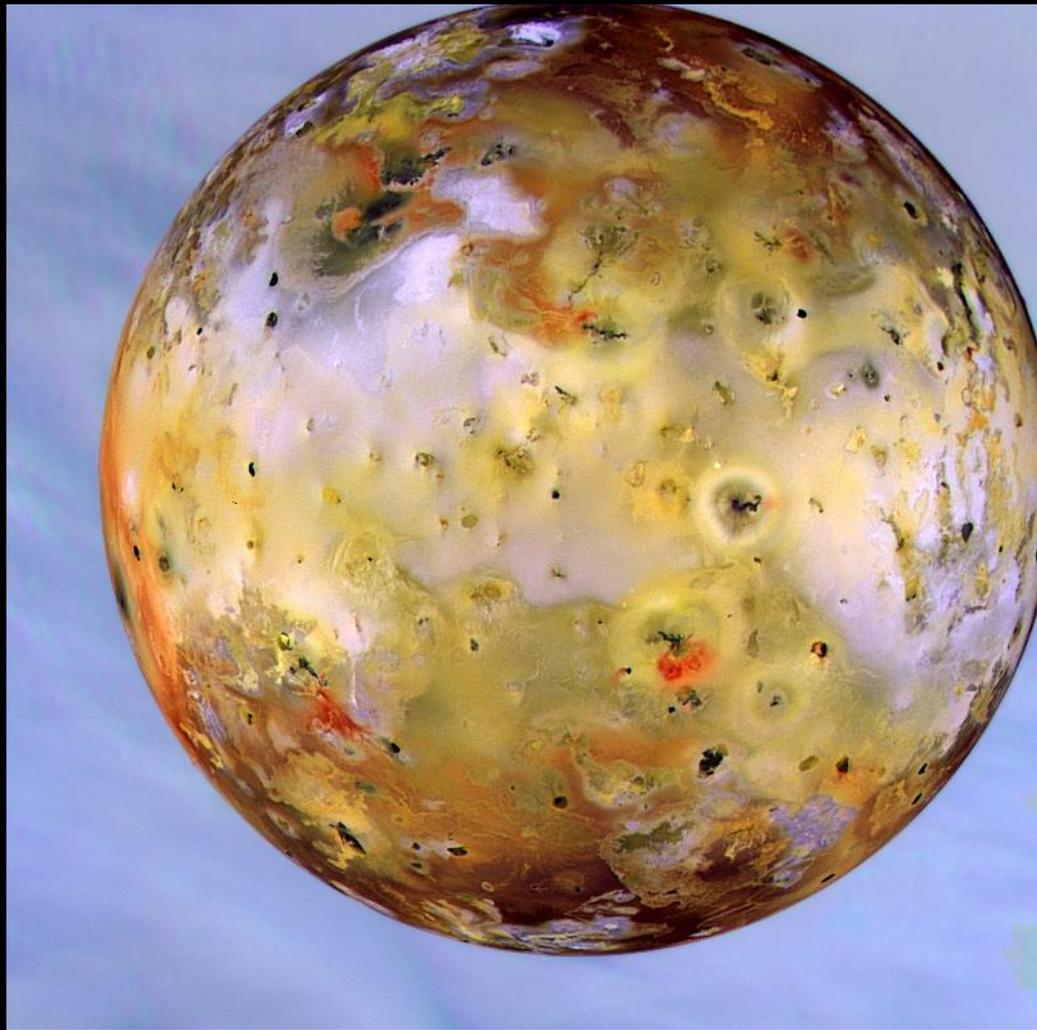
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MCEWEN ET AL.: HIGH-TEMPERATURE HOT SPOTS ON IO



McEwen *et al.* (1997) GRL





Io observations - *Galileo* Europa Mission (GEM) + extension

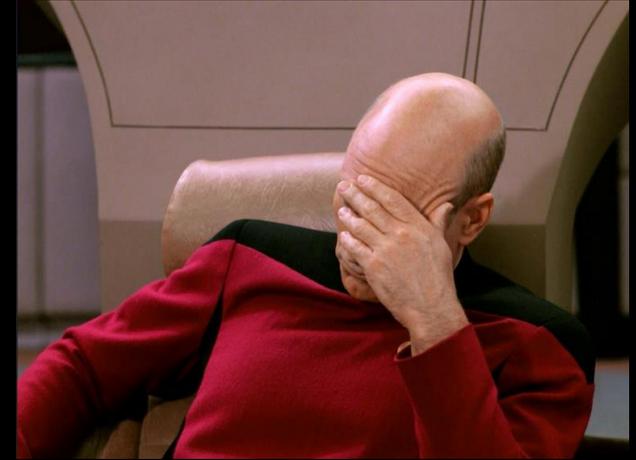
Dec 1997 (E12) to May 2000 (G28)

- Context imagery campaign in the lead up to close Io flybys –
C21, June 1999: SSI, 1.3 km/pixel; NIMS, 65 km/pixel
- The highlight was to be I24, 11 October 1999 – first close flyby since J0

High-spectral resolution NIMS data of Io for the first time

I24, 11 October 1999

- Spacecraft went into safe mode
- The NIMS grating *stuck*
- SSI impacted by radiation...

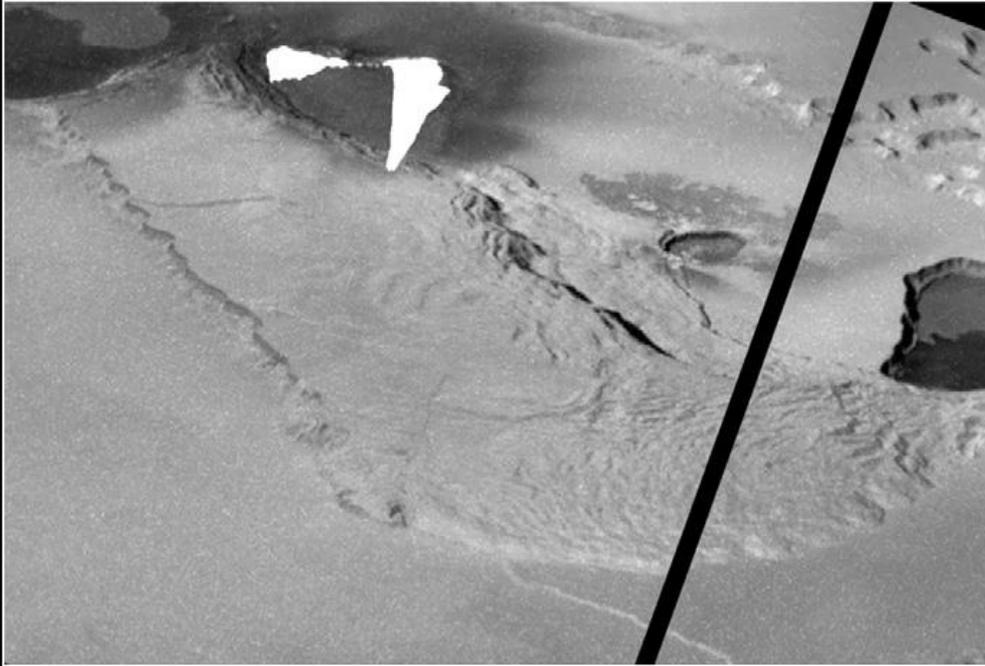


...but some data recovered – see Keszthelyi *et al.* (2001)

I25 – another safing led to data loss, but SSI captured the Tvashtar eruption

I27 – included PPR thermal profiles (Rathbun/Spencer)

Galileo SSI – I25 – November 1999



Keszthelyi *et al.* (2001)

1 km-high lava fountains

25-km long fissure

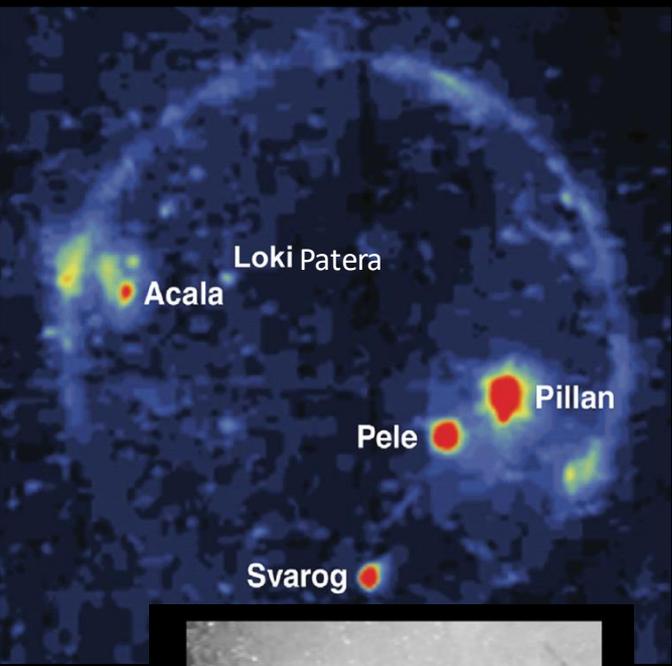
Giant plume

127 data showed these fountains
fed a large lava flow

Very terrestrial-like

Galileo Millennium Mission (GMM) Io observations

- December 2000 (G29) through June 2002 (I33)
- G29 Joint observations with *Cassini*
- I31 NIMS, PPR, SSI
- I32 NIMS, PPR, SSI
- I33 NIMS, SSI data lost (sub-jovian) – only PPR data returned
- A34 Cancelled (but the Encounter Guide and notes are now on the PDS)



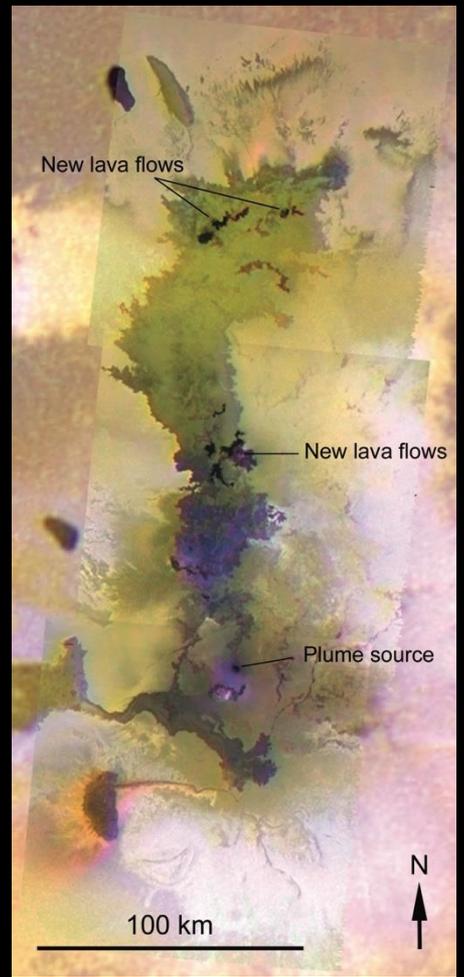
June 1997

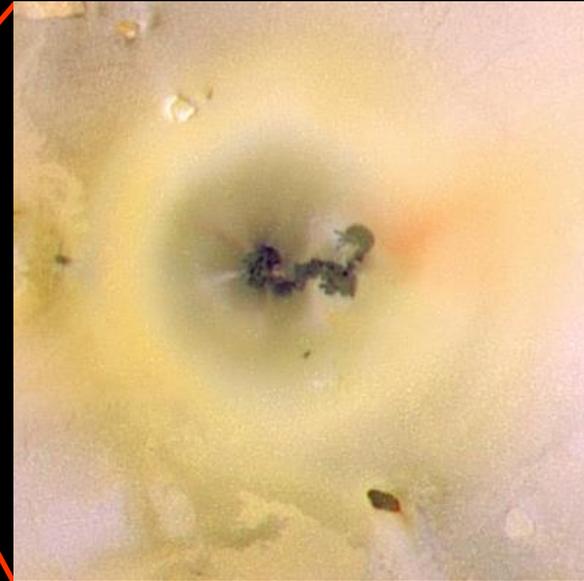
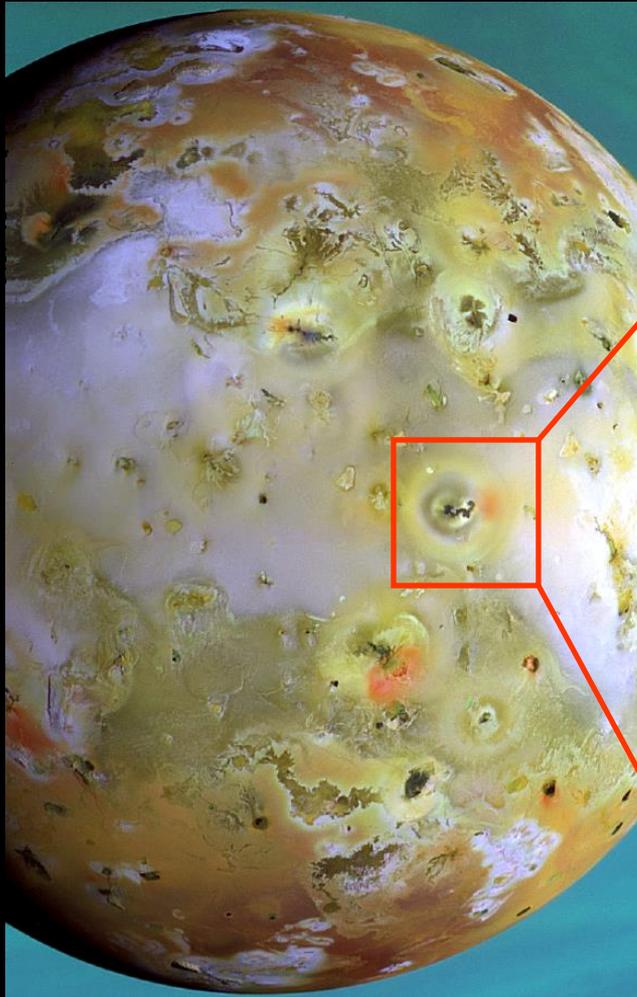


100 km

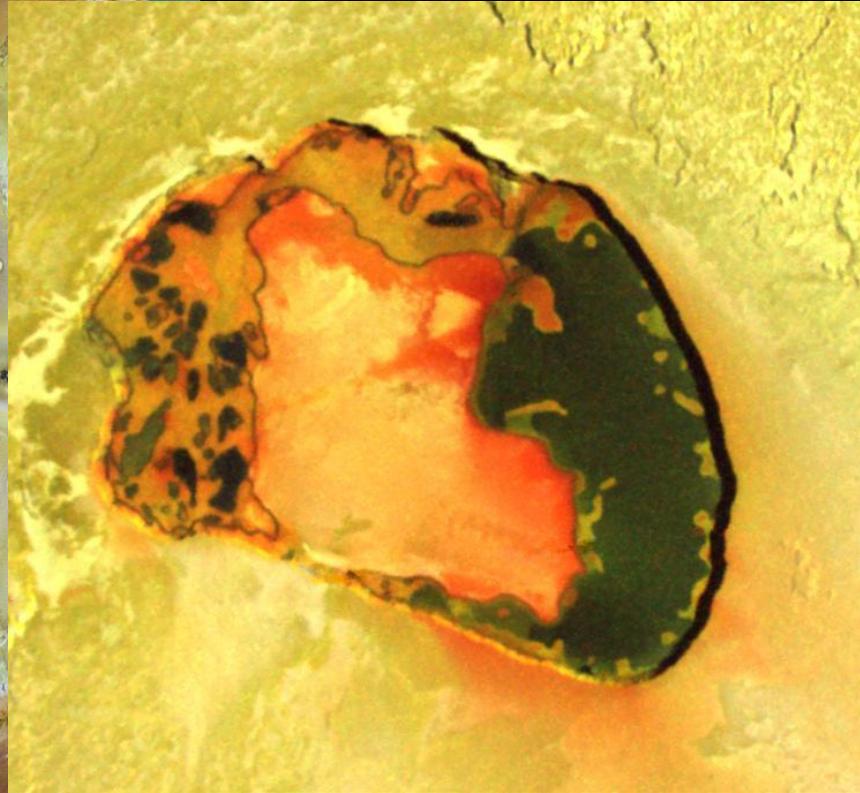


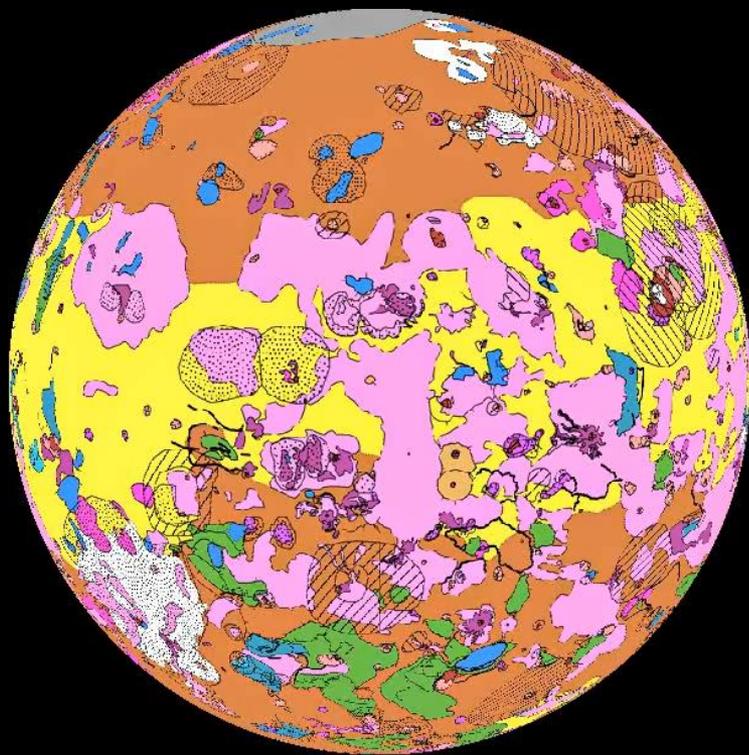
July 1999



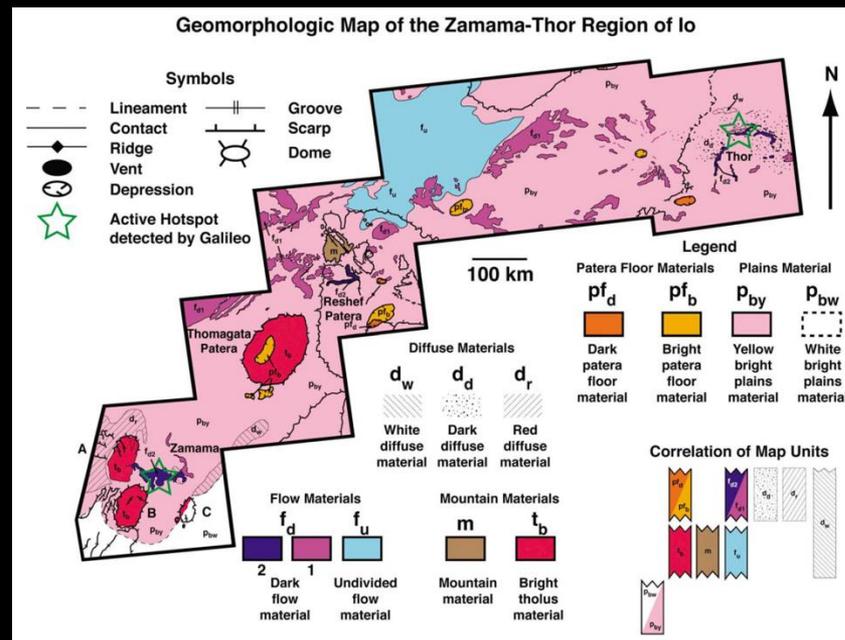


100 km

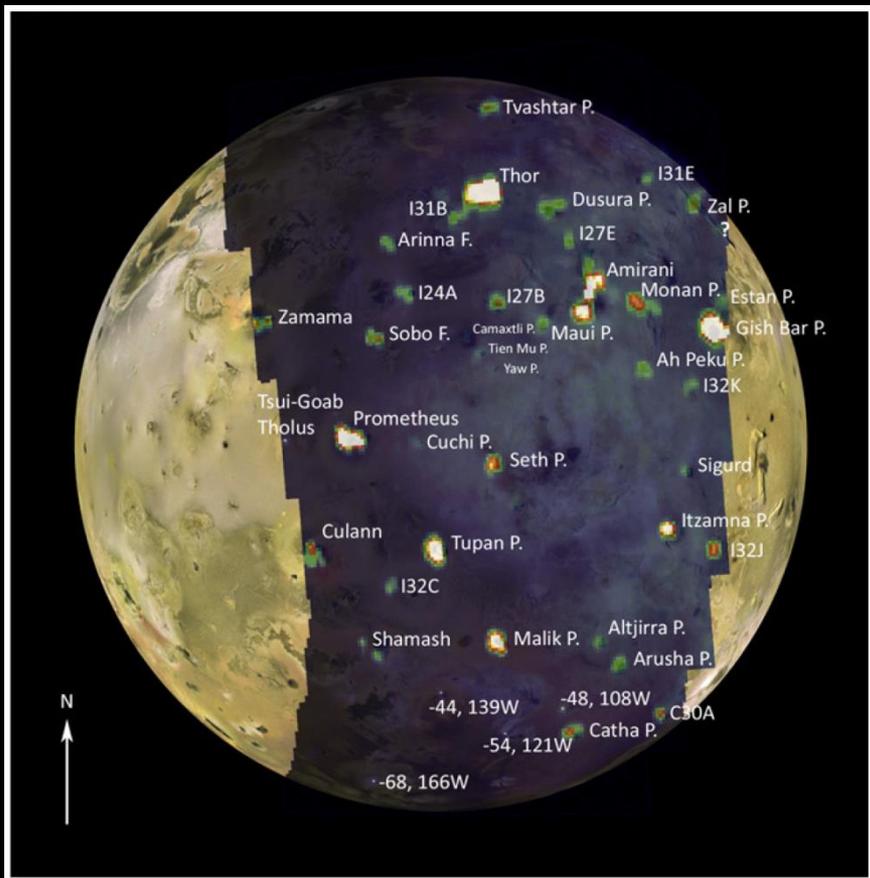




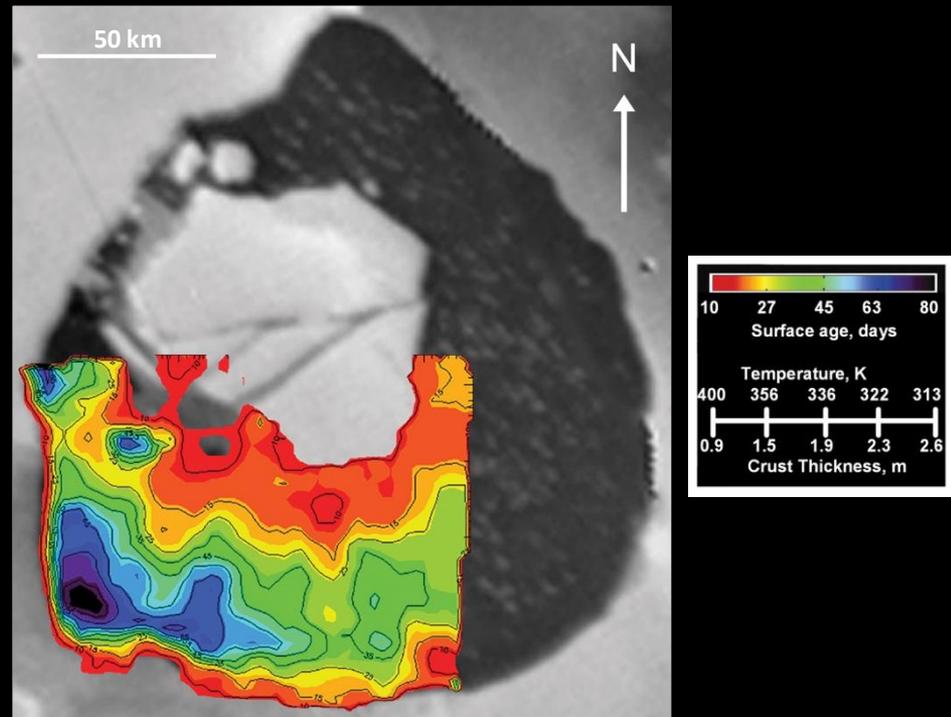
Williams *et al.* (2011) *Icarus*



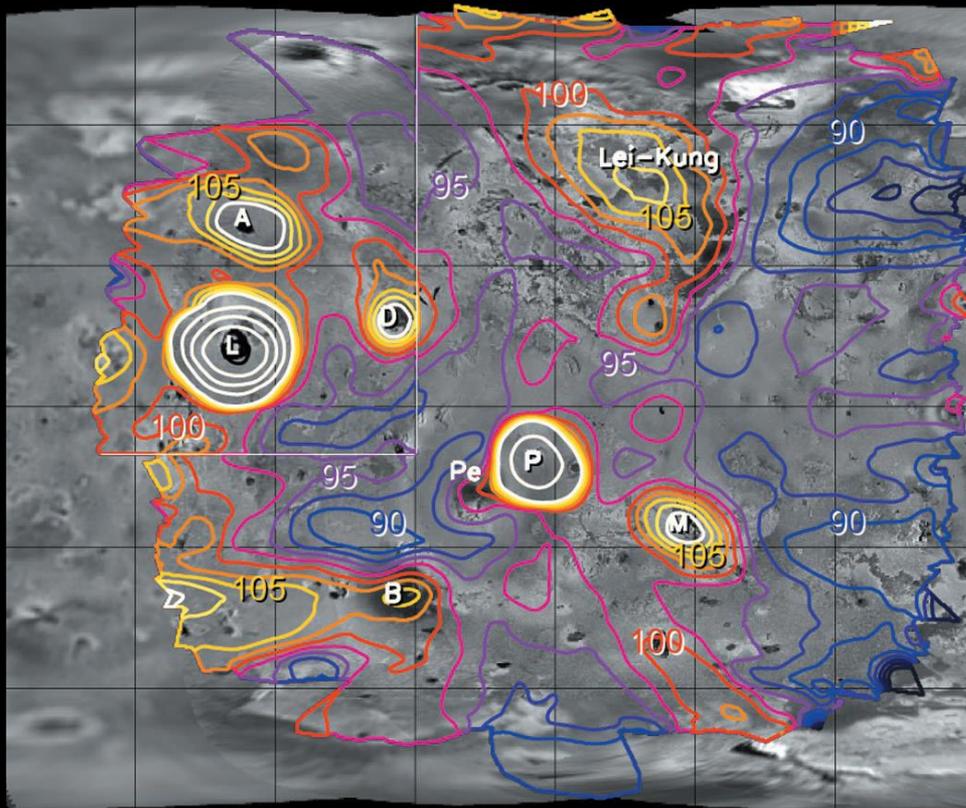
Williams *et al.* (2005) *Icarus*



Veeder et al. (2012) Icarus



Davies (2003) GRL



PPR

Map of Io's background temperature

Determined thermal emission at long wavelengths and from low-T sources

Estimated thermal inertia

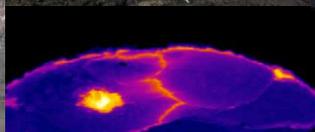
Warm poles

See Rathbun/Spencer papers

Fig. 4. Map of nighttime I27 and I25 (north and west of white line) TB in PPR's wide-open filter superimposed on an SSI map of Io. Contour interval is 2.5 K below 110 K, 20 K above. Notable hot spots include Loki (L), Amaterasu (A), Daedalus (D), Pillan (P), Pele (Pe), Babbar (B), Marduk (M), Lei-Kung Fluctus, and many other fainter sources. Apparent high temperatures near the north pole, and possibly the low temperatures near 170°W, 40°N and 170°W, 30°S, may be spurious edge effects.

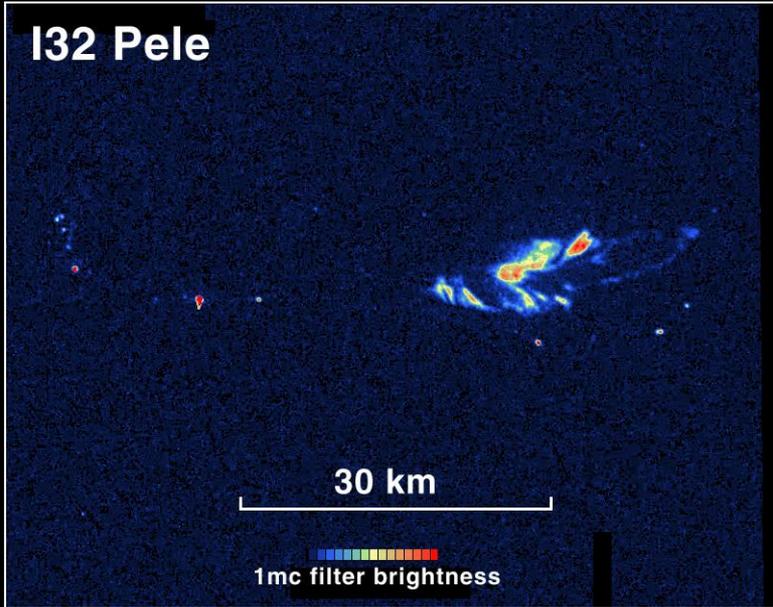
Spencer et al. (2000) *Science*

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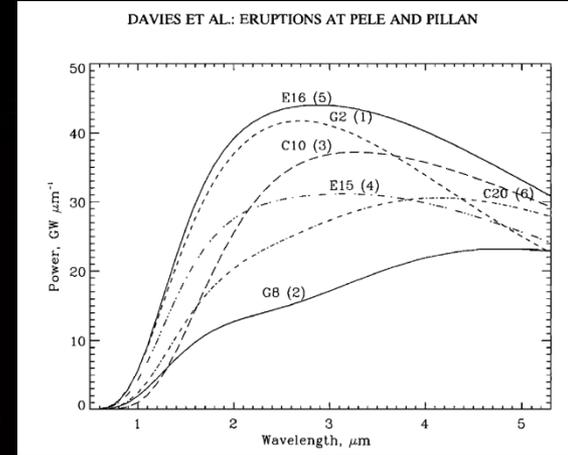
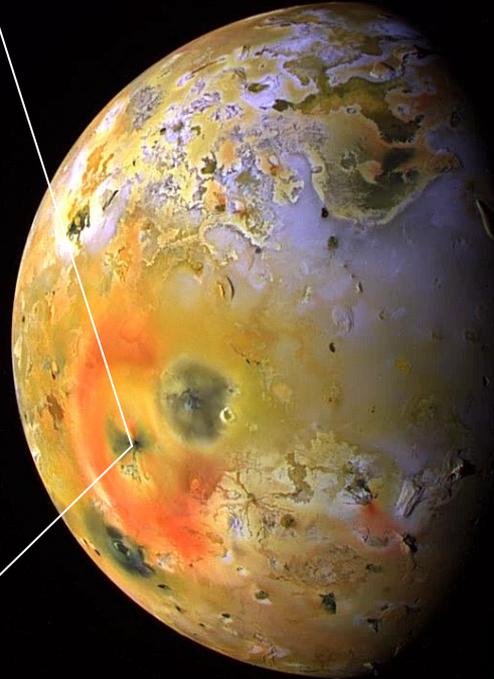
Pele

132 Pele



Galileo SSI observation, 2001

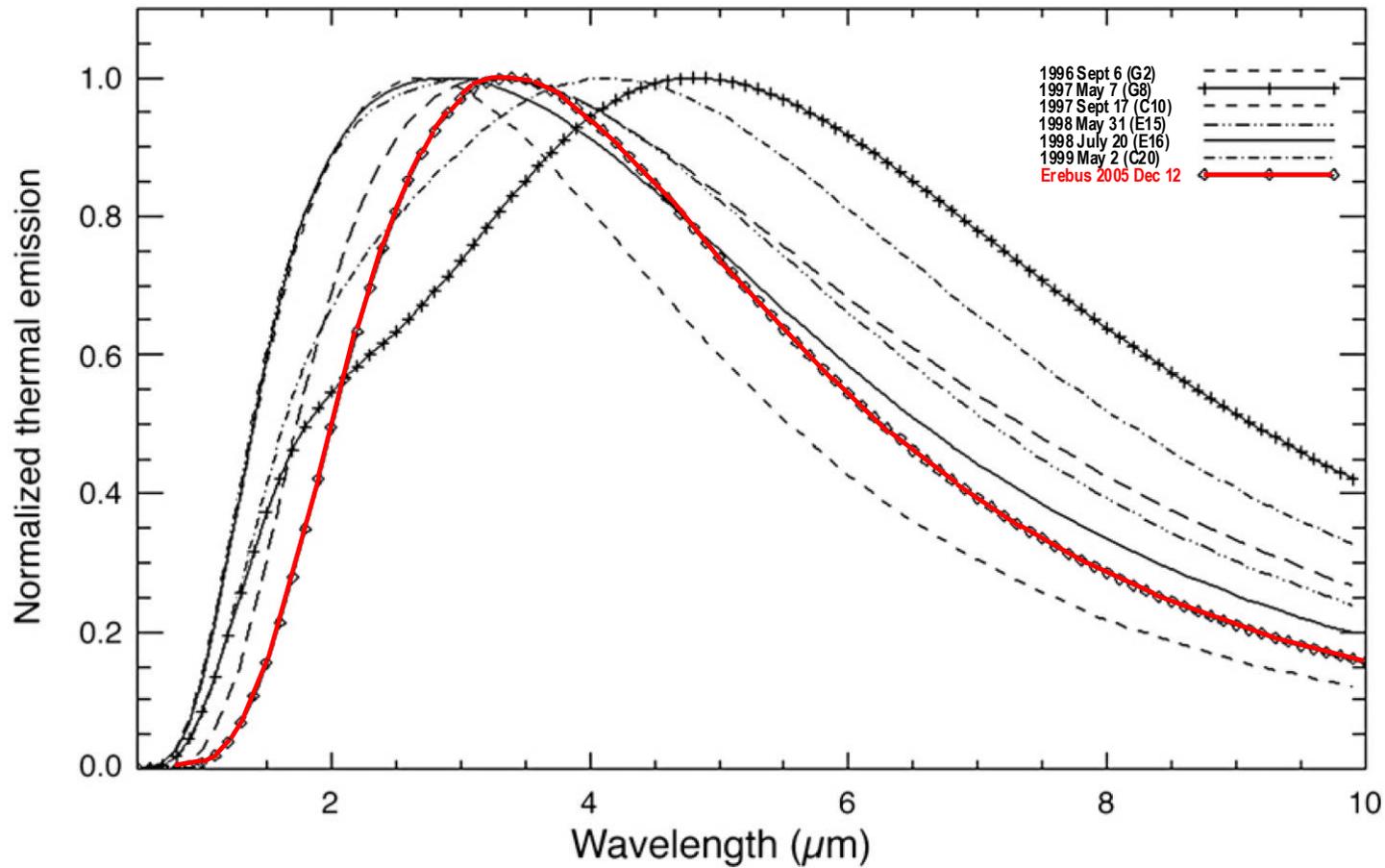
Radebaugh *et al.* (2004) *Icarus*



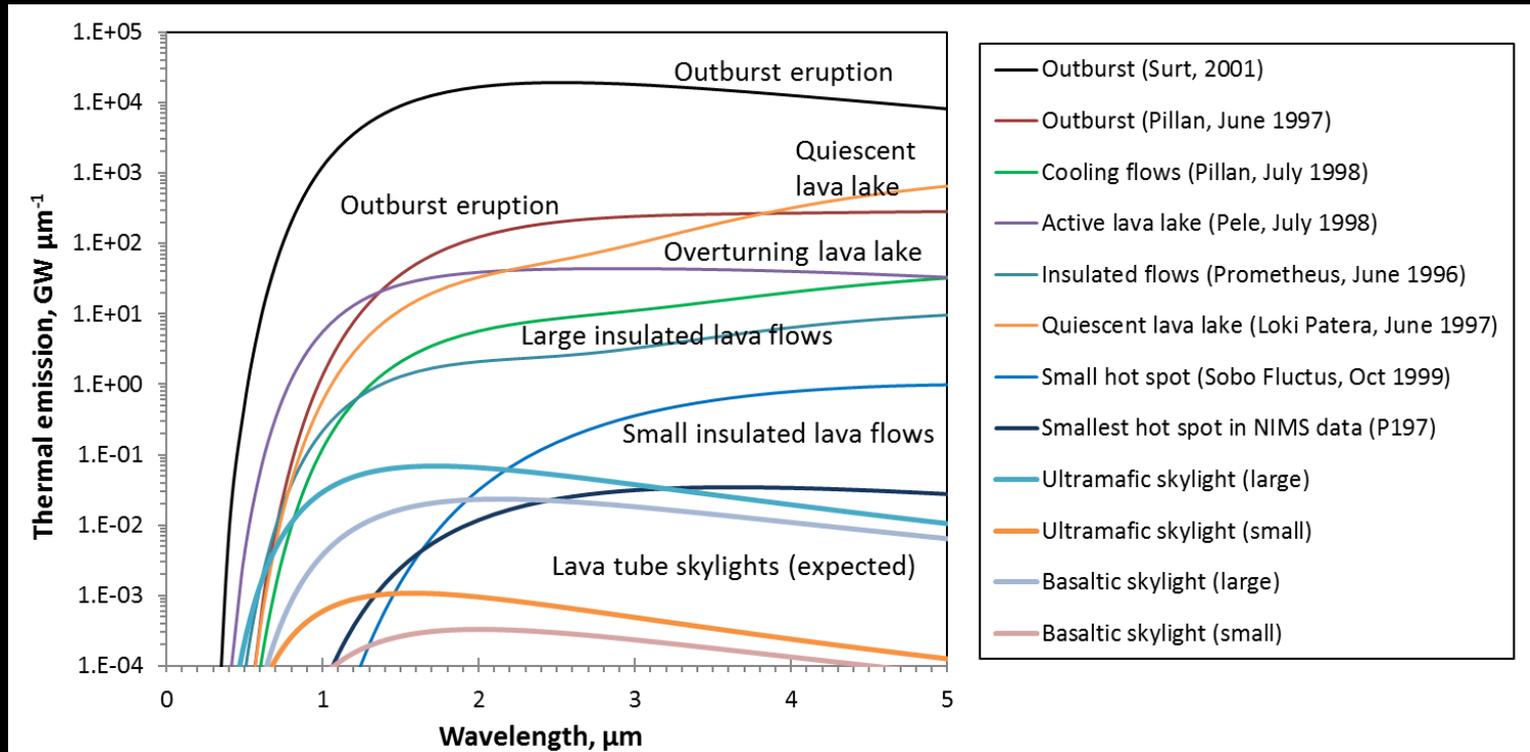
Davies *et al.* (2001) *JGR*

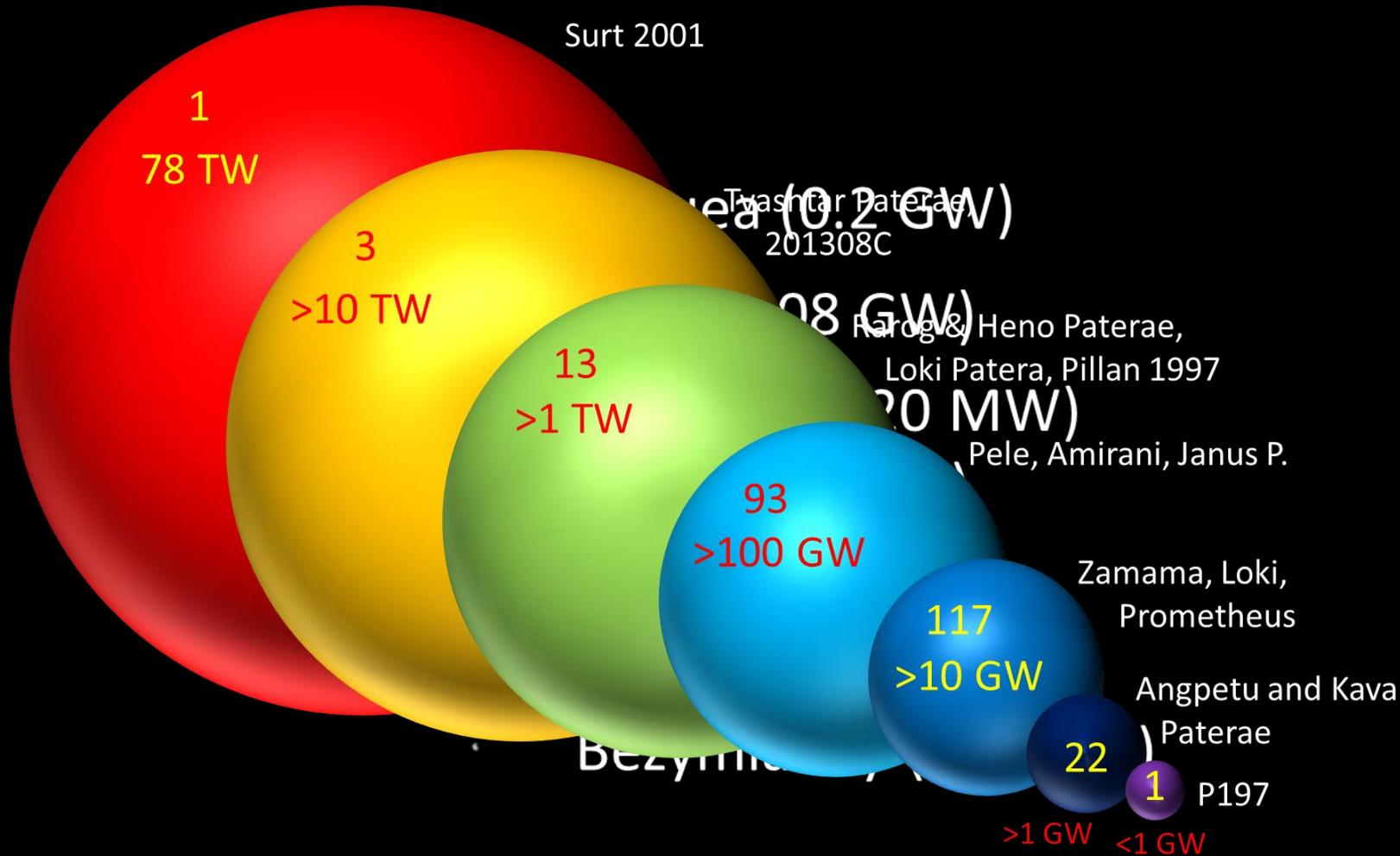
Many lava lakes, in Io's paterae? (Lopes *et al.*, 2004)



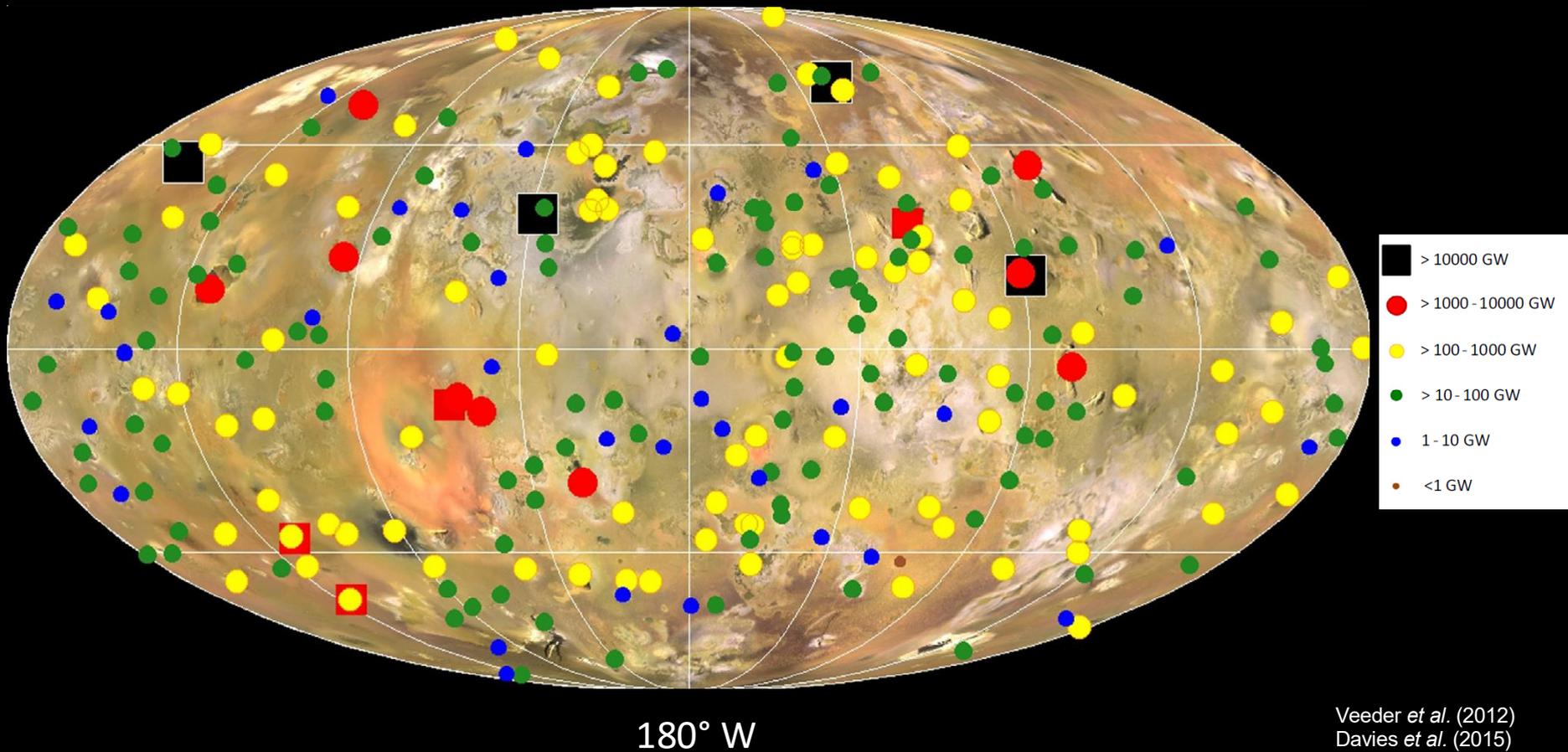


Eruption style and thermal “signature”





Io volcano distribution ranked by thermal emission



Veeder *et al.* (2012)
Davies *et al.* (2015)

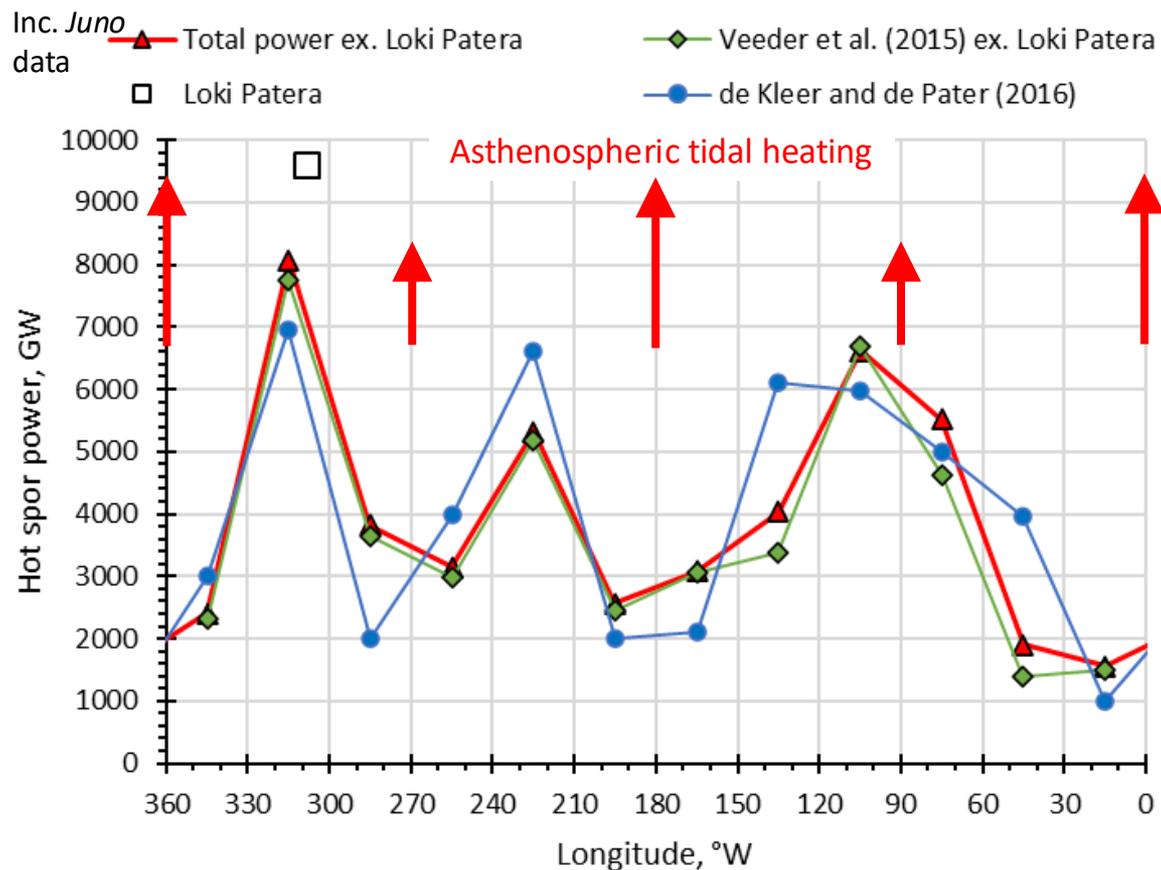
What we learned from *Galileo*

- Numerous surface changes seen, but not as much as expected (Geissler *et al.*, 2004)
- Silicate volcanism dominates (Davies, 2007)
- Heat pipe volcanism likely advection mechanism (Moore, 2001)
- Io's diverse volcanic eruptions and lava products behave like Earth's for the most part, and are broadly basaltic-like... except for scale
- Secondary S, SO₂ volcanism likely (e.g., Lopes *et al.*, 2001; Williams *et al.*, 2001)
- Magnetometer data suggested the presence of a magma ocean (Khurana *et al.*, 2011)

What we learned from *Galileo*

- Volcanic centers and mountains
 - A preponderance of volcanic activity is located within paterae (Veeder *et al.*, 2012)
 - Volcanic centers exhibit a strong preference for formation adjacent to mountains
(Radebaugh *et al.* 2001; Schenk *et al.* 2001; Jaeger *et al.* 2003)
 - On a global scale, there may be subtle variations in the concentrations of mountains and volcanoes (Schenk *et al.* 2001; Kirchoff *et al.* 2011)
- Volcano clusters and heat flow distributions
 - Generally agreed with heat flow patterns predicted by asthenospheric-dominated tidal heating models (Tackley *et al.* 2001; Veeder *et al.* 2012; Beuthe 2013; Hamilton *et al.* 2013; Davies *et al.* 2015)

Longitudinal distribution of volcanic thermal emission from all sources



Io total heat flow: 105 ± 12 TW
(Veeder *et al.*, 1994)

Juno new detections: 1.3 TW

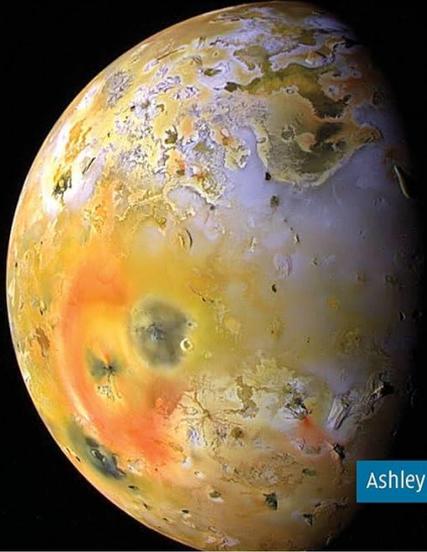
Hot spot heat flow: 58 TW

Io, unmapped: ~ 47 TW
Earth: 47 ± 2 TW
(Davies and Davies, 2010)

CAMBRIDGE PLANETARY SCIENCE

Volcanism on Io

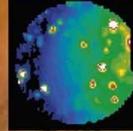
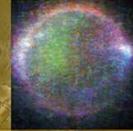
A Comparison with Earth



Ashley Davies

ROSALY M. C. LOPES JOHN R. SPENCER

Io After *Galileo*



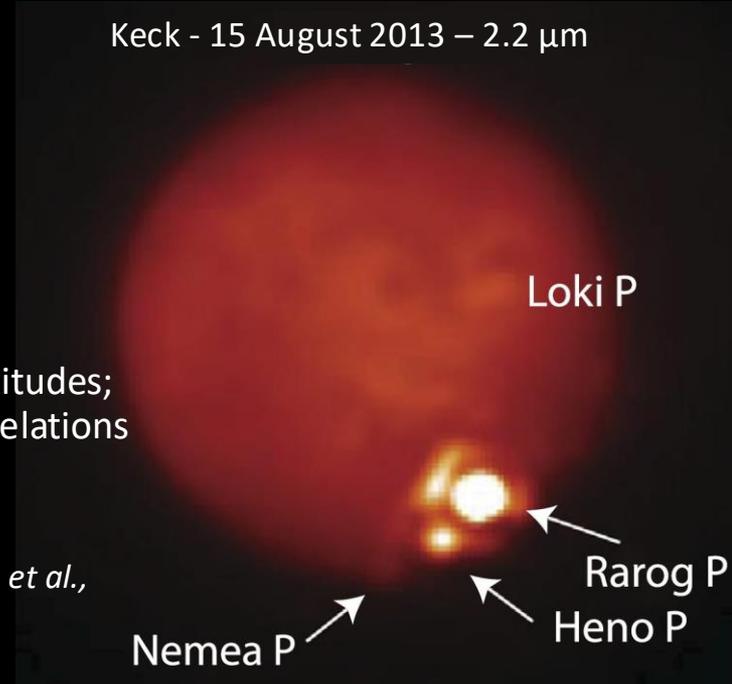
A New View
of
Jupiter's Volcanic
Moon

 Springer

 PRAXIS

What we have learned since *Galileo*

- AO observations: improvements in technology – Keck, SHARK-VIS
 - better spatial, spectral, temporal coverage of volcanic activity
- *Juno* has filled in gaps in polar coverage allowing global accounting of active volcanism for the first time
- Io's polar volcanoes are, on average, less energetic than at lower latitudes; favours asthenospheric/global magma ocean models, although correlations are not strong (Davies *et al.*, 2024)
- *Juno* data do not support a global magma ocean (with caveats) (Park *et al.*, 2024)
- Regions of Io appear to undergo increases in activity, suggesting regional controls are in effect (de Kleer *et al.*, 2019; Davies and Veeder, 2023)



de Pater *et al.* (2014) *Icarus*

See papers by de Pater/de Kleer/Marchis/Cantrall *et al.*

What we have learned since *Galileo*

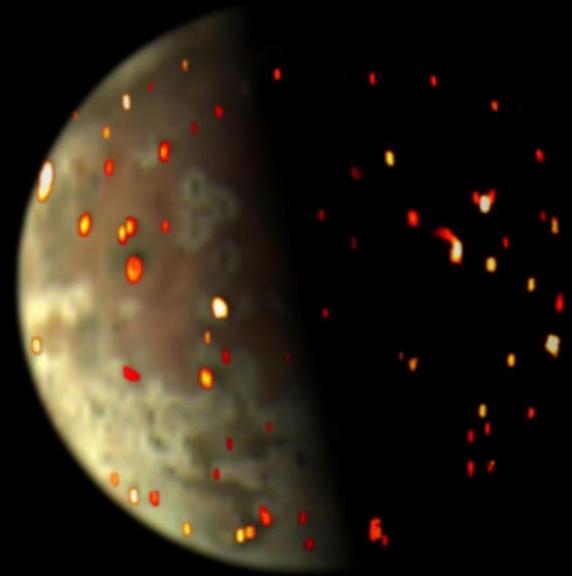
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Davies *et al.* (2025) PSJ

What we have learned since *Galileo*

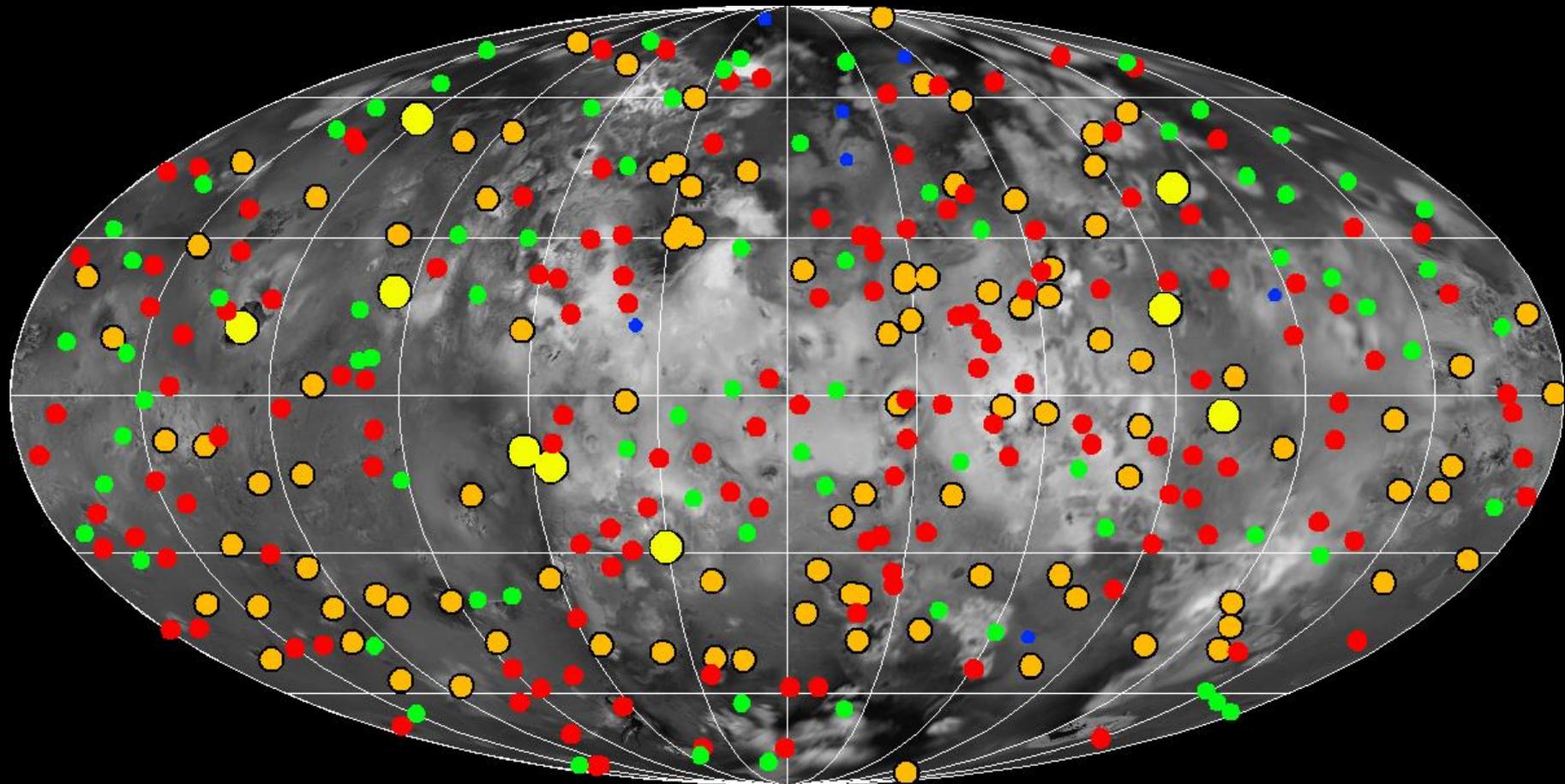
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- Io's polar volcanoes are, on average, less energetic than at lower latitudes; favours asthenospheric/global magma ocean models, although correlations are not strong (Davies *et al.*, 2024)
- *Juno* data do not support a global magma ocean (with caveats) (Park *et al.*, 2024)
- Regions of Io appear to undergo increases in activity, suggesting regional controls are in effect (de Kleer *et al.*, 2019; Davies and Veeder, 2023)



NASA/JPL-Caltech/SwRI/ASI/INAF/JIRAM

180 °W

Davies et al. (2024) PSJ



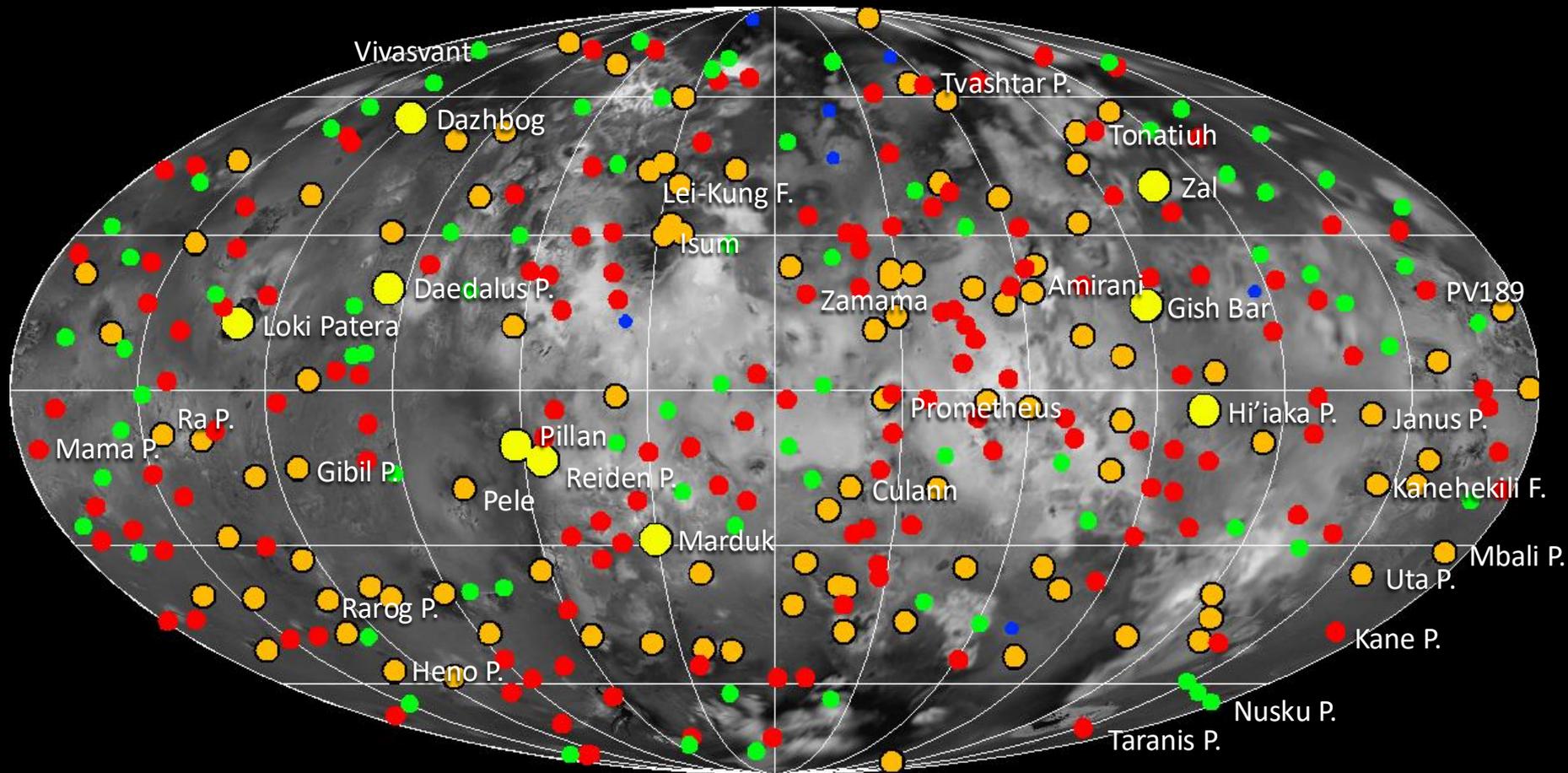
• <1 GW

• >1 to 10 GW

• >10 to 100 GW

• >100 to 1000 GW

• >1000 to 10000 GW



<1 GW

>1 to 10 GW

>10 to 100 GW

>100 to 1000 GW

>1000 to 10000 GW

What we still don't know

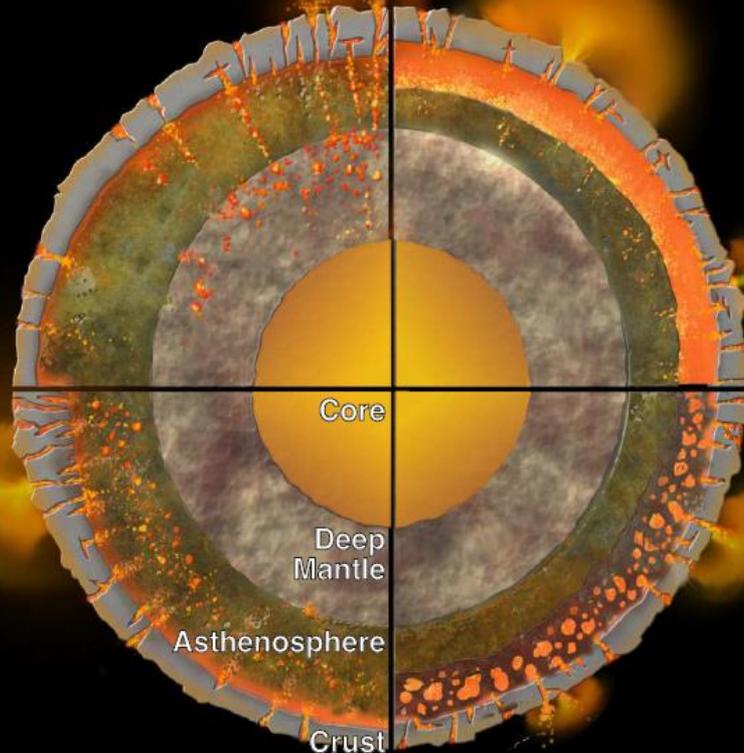
- Heat flow – what is happening at the poles?
- Pattern and magnitude of endogenic heat flow away from hot spots
- Composition of lavas – range? Distribution?
- No global magma ocean? Could be deep/partial/thin? A porous medium? Mushy?
- Thickness of lithosphere? Does this vary?
- Size of core?
- What is the relationship between volcanic activity and activity in the tori?
- How to resolve differences in the pattern of observed volcanism and tidal heating models?
- On a local level – what makes Loki Patera persist?

Solid-body dissipation in the deep mantle

- Heating and melting concentrate in the deep mantle
- Weak magnetic induction
- Polar focused volcanism
- High temperature magma
- Low k_2 and libration amplitude

Solid-body dissipation in the asthenosphere

- Heating and melting concentrate in the asthenosphere
- Weak magnetic induction
- Low latitude focused volcanism
- Lower temperature magma
- Low k_2 and libration amplitude

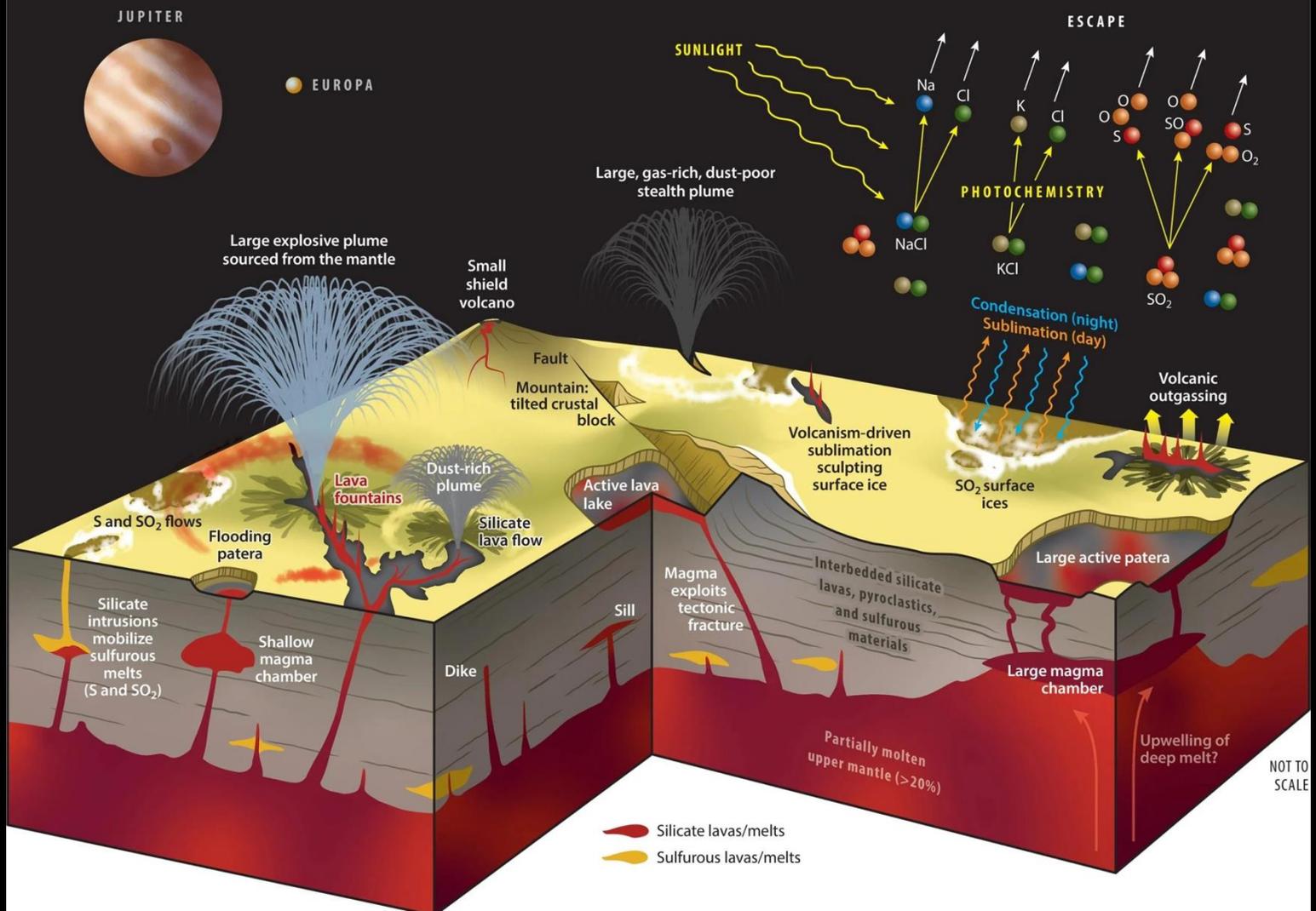


Fluid-body dissipation in a “magma ocean”

- Heating and melting concentrate in the asthenosphere
- Volcanism may be focused at low latitudes with a longitudinal shift to the East
- High temperature magma
- High k_2 and libration amplitude

Fluid-body dissipation in a “magmatic sponge”

- Heating and melting concentrate in the asthenosphere
- Volcanism may be focused at low latitudes
- Low to high temperature magma
- Low k_2 and libration amplitude



JUPITER

EUROPA

SUNLIGHT

ESCAPE

PHOTOCHEMISTRY

Condensation (night)
Sublimation (day)

Volcanic outgassing

SO₂ surface ices

Volcanism-driven sublimation sculpting surface ice

Large, gas-rich, dust-poor stealth plume

Large explosive plume sourced from the mantle

Small shield volcano

Fault

Mountain: tilted crustal block

Active lava lake

Sulfate-rich plume

Silicate lava flow

Lava fountains

Sand and SO₂ flows

Flooding patera

Shallow magma chamber

Sill

Dike

Interbedded silicate lavas, pyroclastics, and sulfurous materials

Large active patera

Large magma chamber

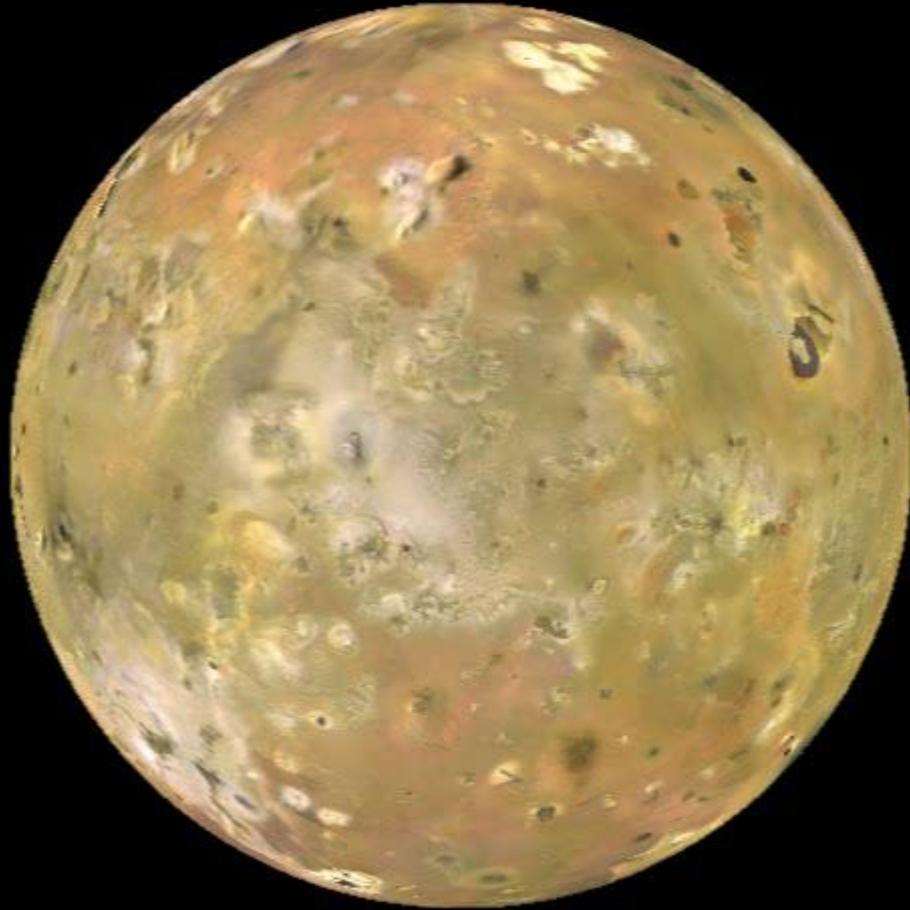
Upwelling of deep melt?

Partially molten upper mantle (>20%)

Silicate lavas/melts
Sulfurous lavas/melts

NOT TO SCALE





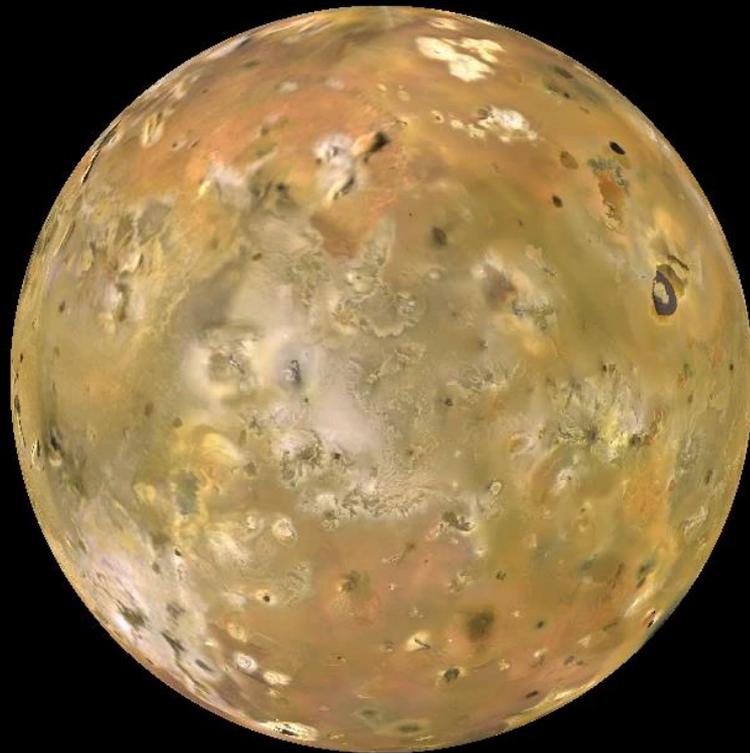
Voyager-Galileo mosaic (Becker et al., 2005)

End

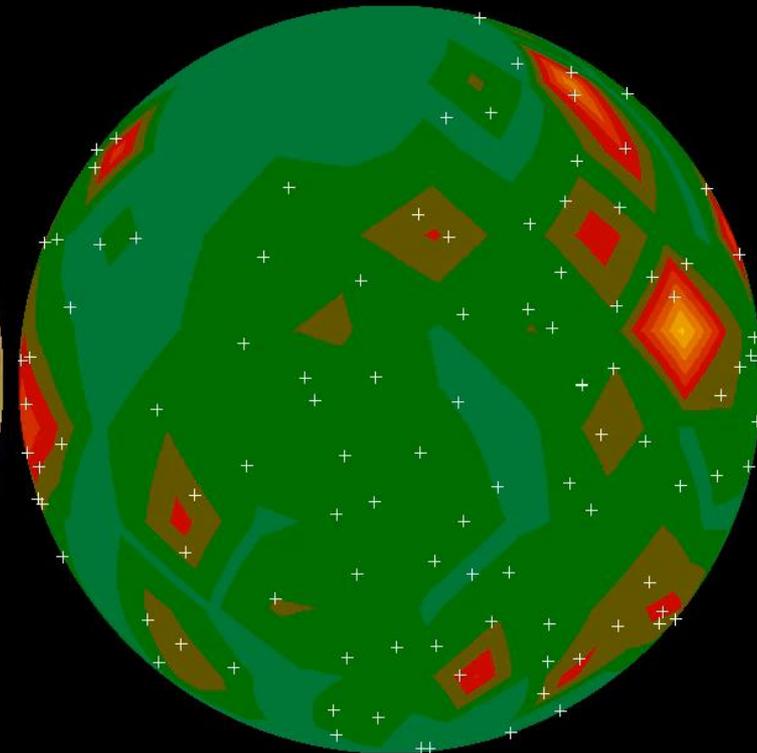


Backup material

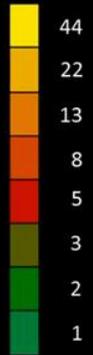
Io volcanoes and heat flow



0°W



Heat Flow
W/m²



+ = hot spot

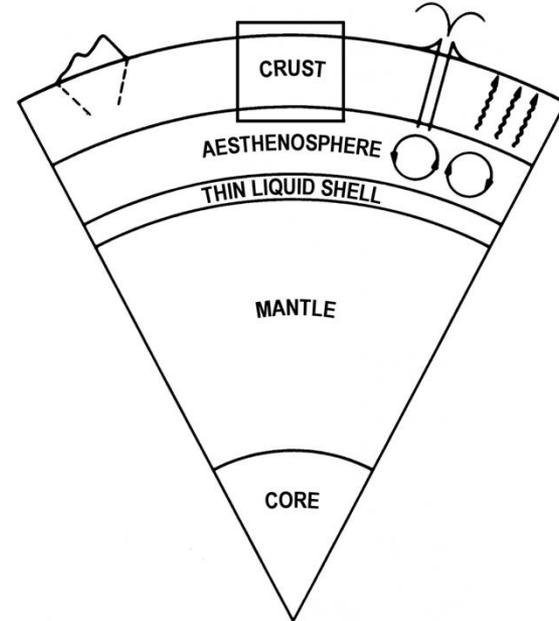
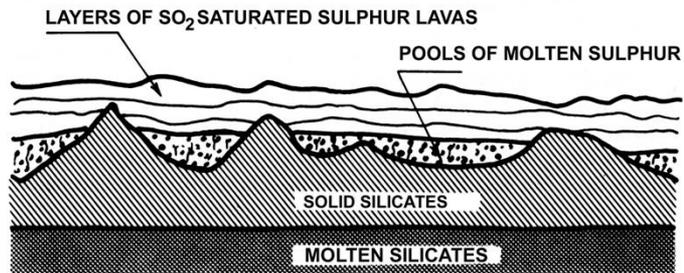
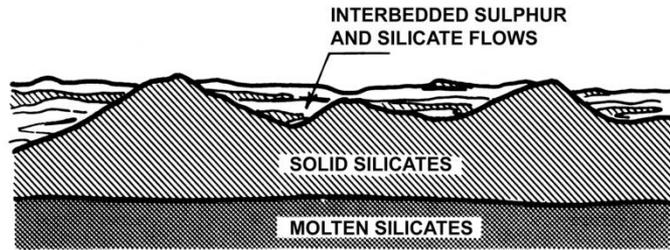


Table 5*The Thermal Signature and Evolution of Different Eruption Modes on Io and Earth*

	Eruption type	Location	Thermal characteristics	Short-timeframe change	Long-timeframe change
	Strombolian-type explosion	Fixed	Intense short-wavelength thermal emission Very high flux densities Highest color temperature	Very short duration (seconds)	Rapid decrease in thermal signal to minimal levels in minutes
	Lava fountains	Fixed	Intense short-wavelength thermal emission. Very high radiant flux densities Highest color temperature	Very short duration (~hours?)	Not seen unless event repeats: series of thermal spikes
	Lava lake	Fixed	Intense-to-moderate short-wavelength thermal emission Variable radiant flux density Variable color temperature	Brief periods of overturning and enhanced thermal activity	Persistent hot-spot
	Channelized flows	Wandering	High-to-moderate short-wavelength thermal emission and radiant flux density. High color temperature down axis of channel and where flow is turbulent	Thermal source increases in size (lengthens) and undergoes surges	Flows eventually stop and cool



Insulated and tube fed flows ('a'a and pahoehoe flows)

Wandering, persistent thermal source

Low short-wavelength thermal emission
 Low radiant flux density
 Low color temperature. High temperature sources along flow from skylights and breakouts are common on Earth and likely on Io

Source increases in area and changes location

Location migrates, intensity varies, sometimes episodically. Peak thermal flux often away from vent but linked to vent by sinuous feature of extremely low thermal intensity (tube)



Lava domes

Fixed. Gradual increase in size

Low short-wavelength thermal emission
 Low radiant flux densities
 Very low color temperature

Small incandescent areas: occasional explosive activity suddenly increases thermal emission.

Weeks-months-years
 Not identified on Io



Silicic lava flows

Gradual increase in size

Low-to-no short-wavelength thermal emission
 Extremely low flux densities
 Extremely low color temperature

Very stable

Years
 Not identified on Io

Note. Color temperature is the temperature at which a black body would emit radiation of the same color as a given object. Image credits: Stromboliian explosion: USGS. Lava fountain: P. Mouginis-Mark. Lava lake: P. Vetsch. Open channel flow: US Nat. Park Service, S. Lopez. Pahoehoe flows: A. G. Davies. Lava dome: L. P. Keszthelyi. Silicic flow: A. J. L. Harris. Table modified from Davies et al. (2010).

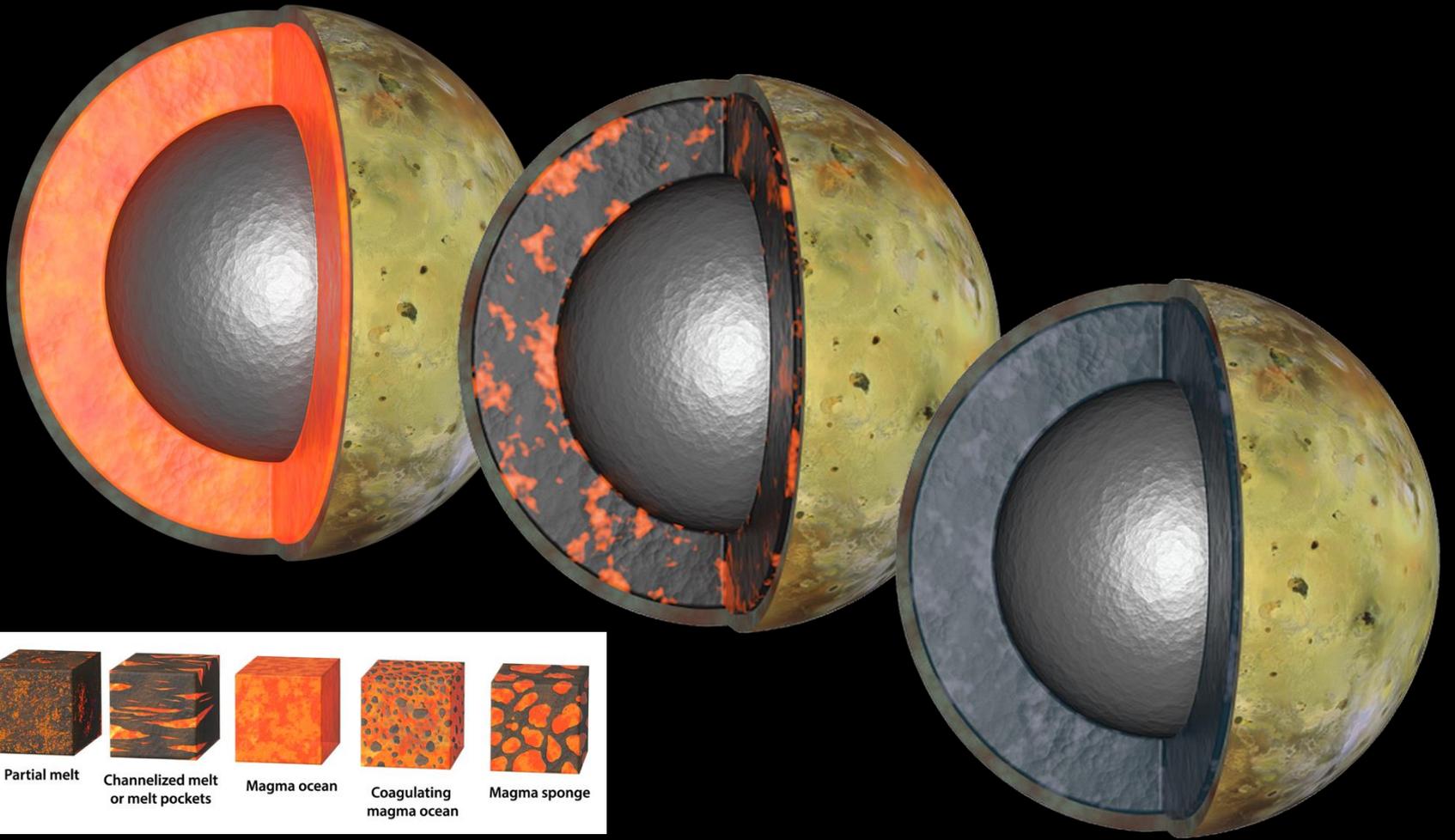
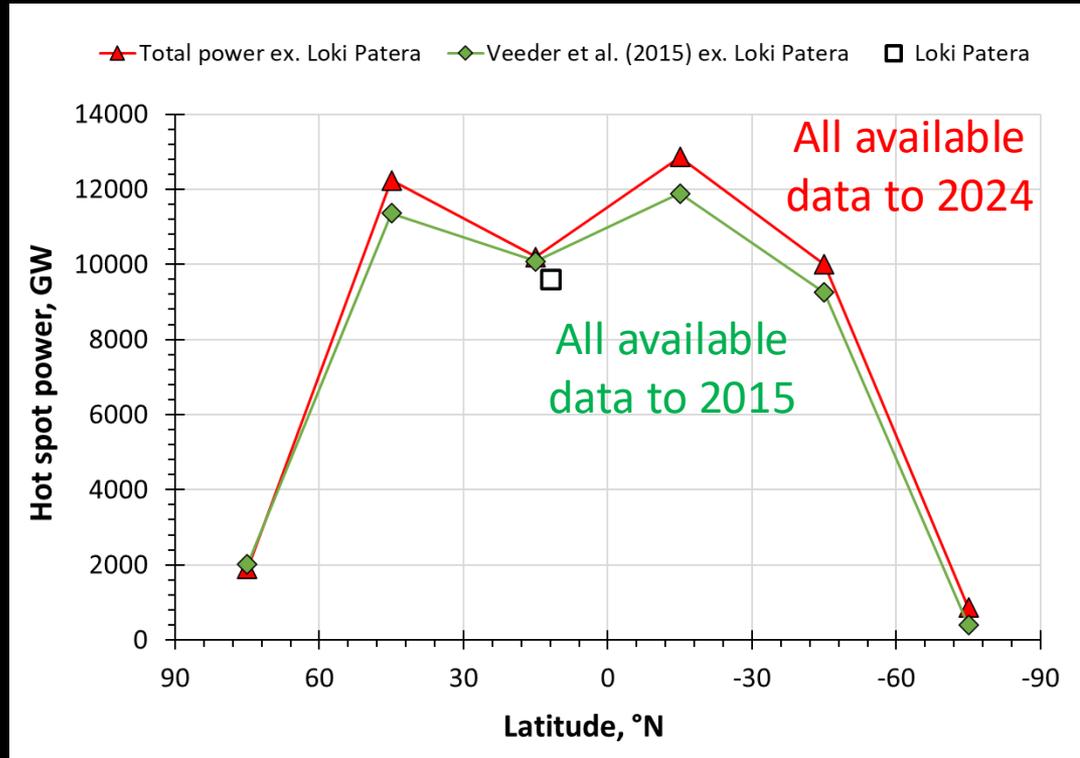


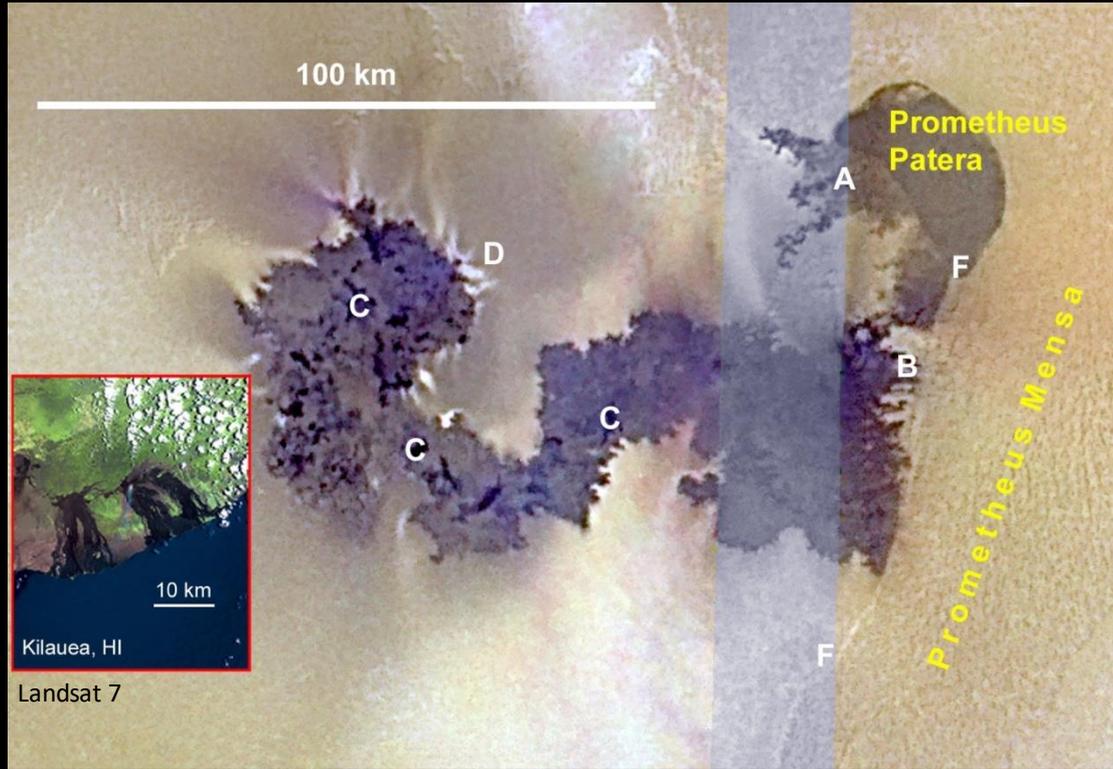
Image credits: Chuck Carter and James Tuttle Keane / Keck Institute for Space Studies.

Latitudinal distribution of total thermal emission volcanic thermal emission



Davies et al. (2024) *PSJ*

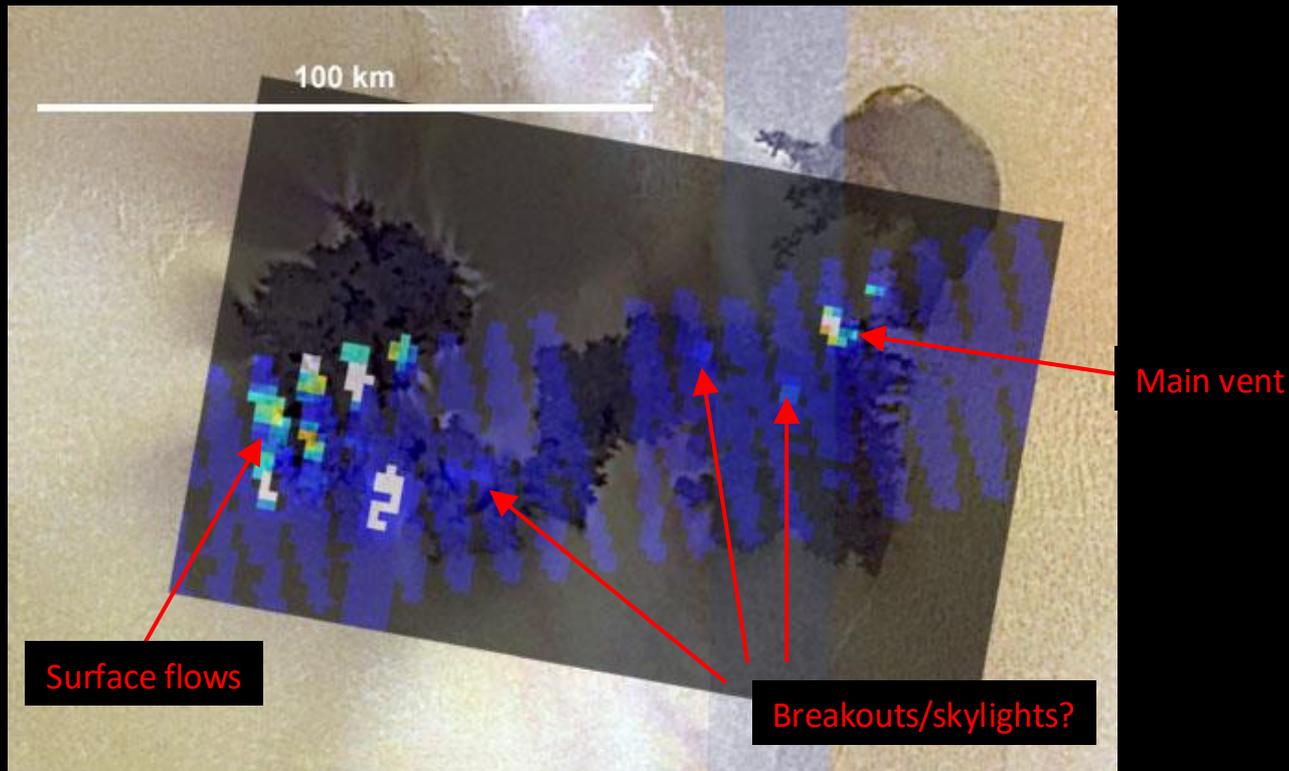
Prometheus – tube-fed lava flows



Galileo SSI image
McEwen et al. (1998); Keszthelyi et al. (2001)

Davies et al. (2006) *Icarus*

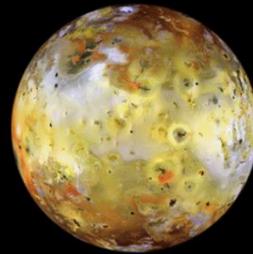
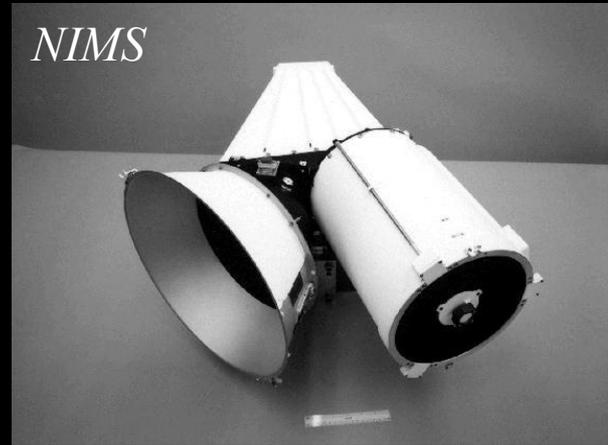
Prometheus – tube-fed lava flows



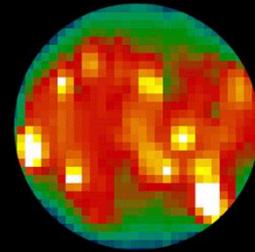
NIMS: 24INPROMTH91A 11 Oct 1999
Average spatial resolution: 1.4 km/pixel

Leone et al. (2009) *Icarus*

NASA *Galileo* mission – 1995-2003



Visible



Infrared