Io as a Target for Future Exploration

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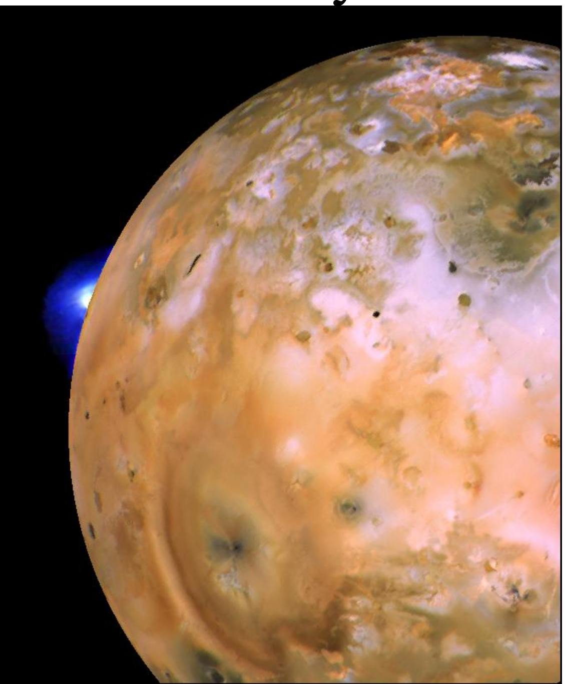
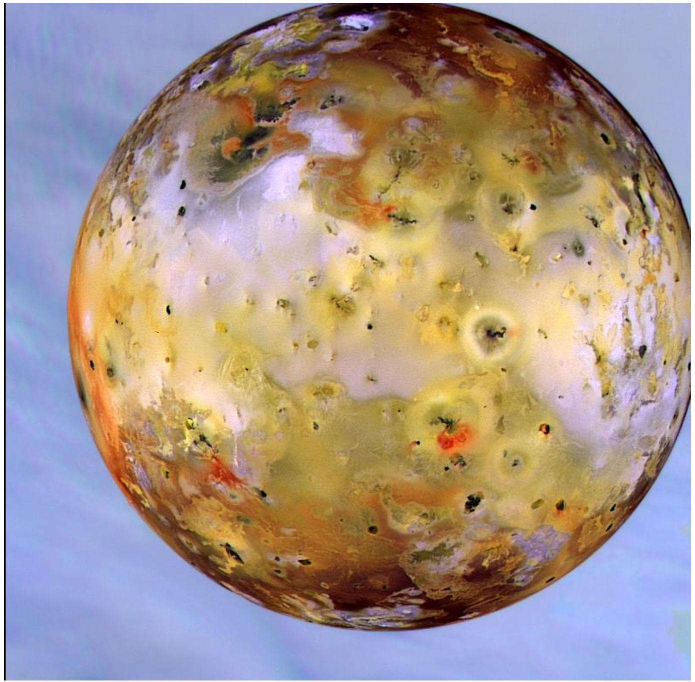
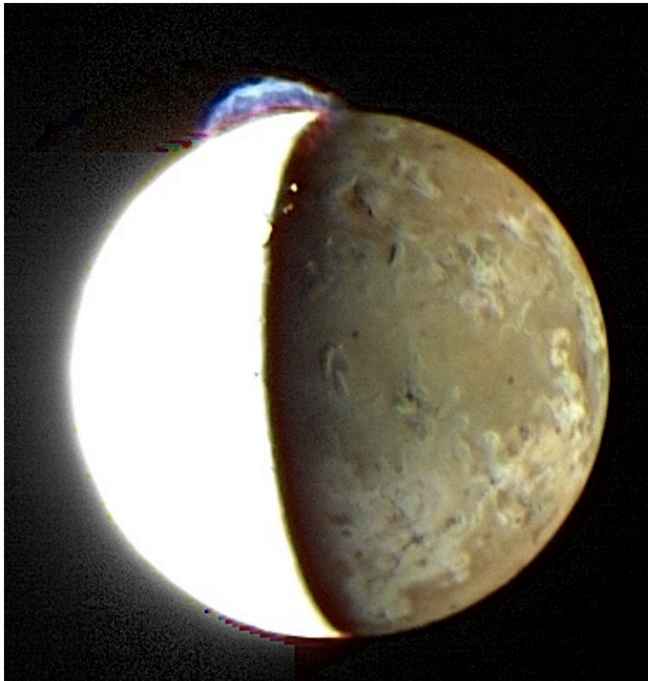
Io: the most volcanically active body is solar system

• Best example of tidal heating in solar system; linchpin for understanding thermal evolution of Europa

• Effects reach far beyond Io: material from Io feeds torus around Jupiter, implants material on Europa, causes aurorae on Jupiter

• Analog for some exoplanets – some have been suggested to be volcanically active

OPAG recommendation #8 (2016): OPAG urges NASA PSD to convene an Io Observer SDT to steer a comprehensive mission concept study for the next Decadal Survey

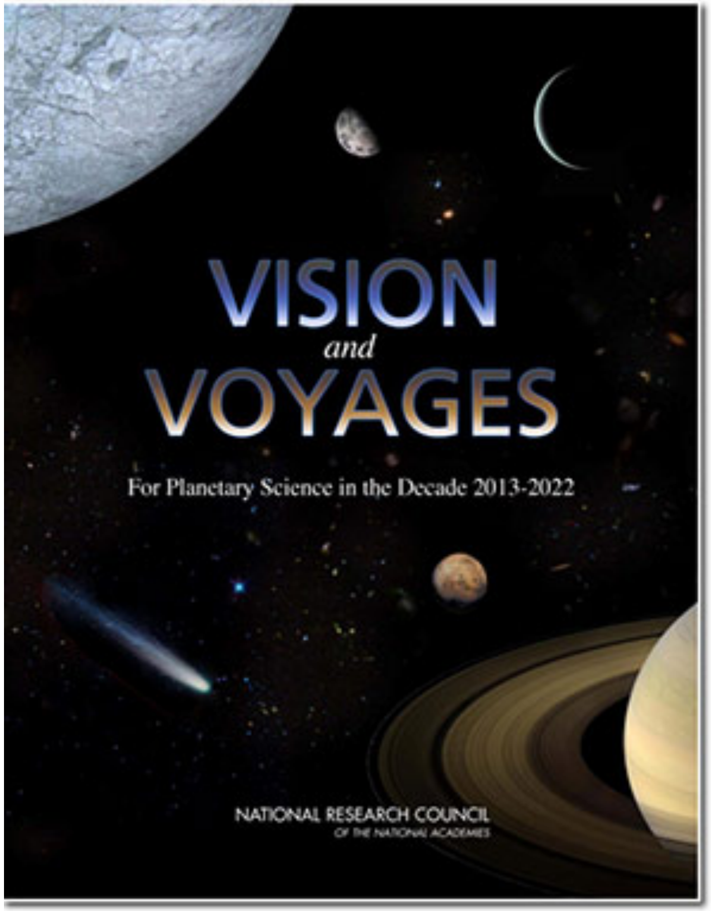
- An *Io Observer* mission was listed in NF-3, Decadal Survey 2003, the NOSSE report (2008), Visions and Voyages Decadal Survey 2013 (for inclusion in the NF-5 AO)

- *Io Observer* is a high OPAG priority for inclusion in the next Decadal Survey and a mission study is an important first step

- This study should be conducted before next Decadal and NF-5 AO and should include:
  - recent advances in technology provided by Europa and Juno missions
  - advances in ground-based techniques for observing Io
  - new resources to study Io in future, including JWST, small sats, miniaturized instruments, JUICE

Most recent study: Decadal Survey Io Observer (2010) (Turtle, Spencer, Khurana, Nimmo)

- A mission to explore Io's active volcanism and interior structure (including determining whether Io has a magma ocean) and implications for the tidal evolution of the Jupiter-Io-Europa-Ganymede system and ancient volcanic processes on the terrestrial planets.
- This mission would most likely be a New-Frontiers-class Jupiter orbiter with multiple Io flybys.
- Science goals derived from NOSSE (New Opportunities in Solar System Exploration report (Beebe et al., 2008)

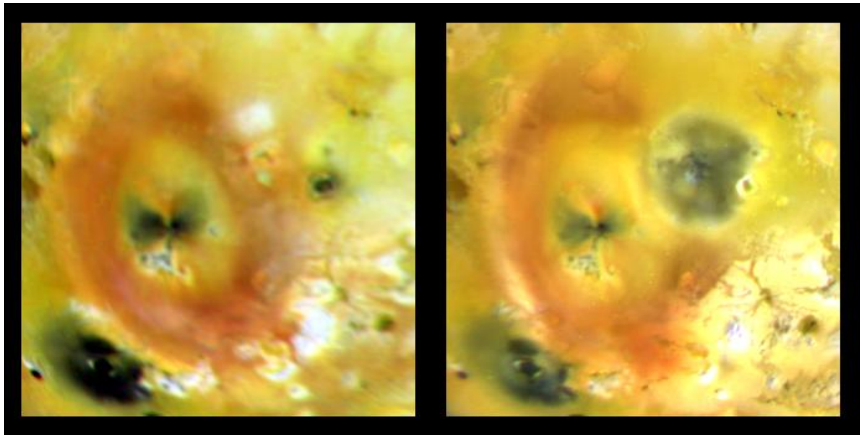


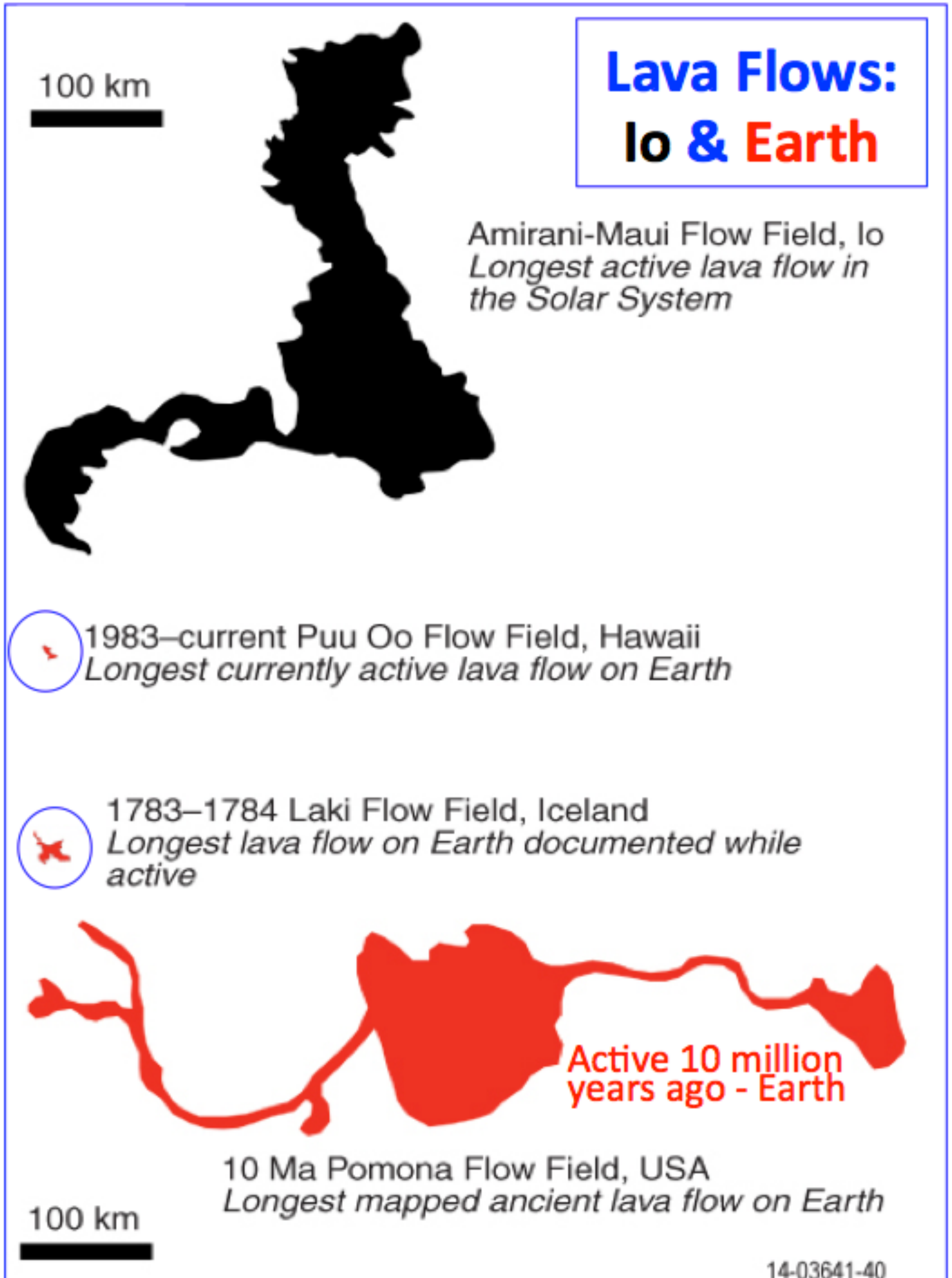
Science Goals: active volcanism

NOSSE Goal 1: Understand the eruption mechanisms for Io's lavas and plumes and their implications for volcanic processes on Earth, especially early in Earth's history when its heat flow was similar to Io's, and elsewhere in the solar system. *(and exoplanets)*

- *Very high rates of volcanism were common in the early history of the solar system and large volcanic provinces are seen on Earth, Venus, Mars, Mercury, Moon, perhaps exoplanets*
- *Io is an extreme case of a volcanically active world that provides a template for how much volcanism can affect planetary evolution.*

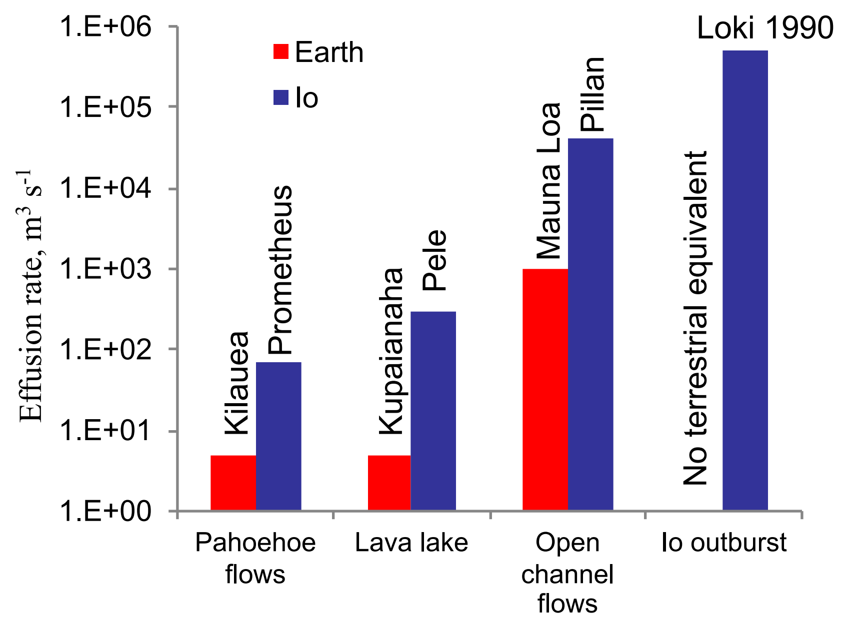
V&V Objective A1:
Test and revise models for active volcanic processes on Io.



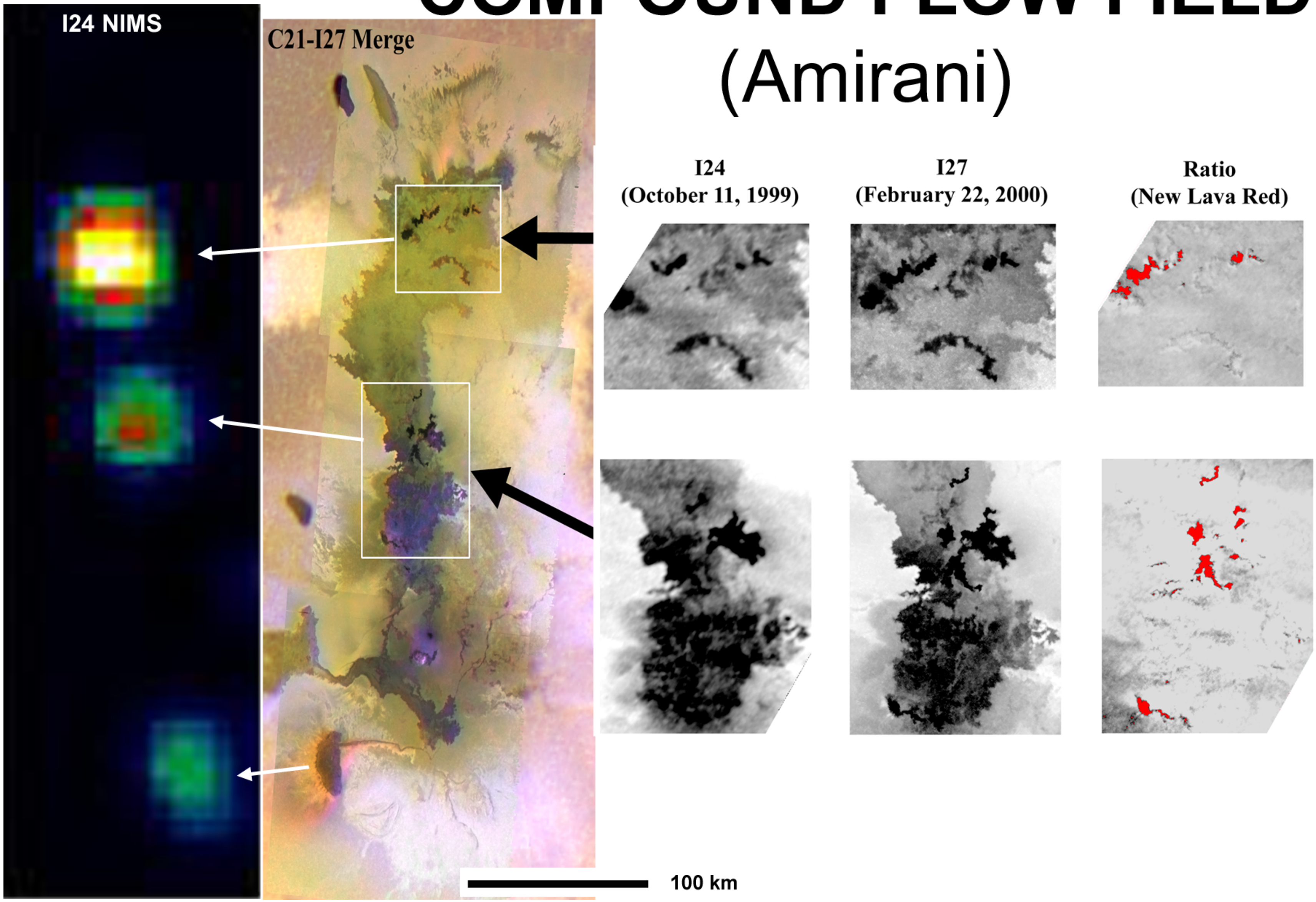


- Effusion rates 10-100x greater on Io than on Earth (today) for comparable eruption styles, a window into Earth's past
- Io allows us to directly observe the formation of giant lava flows and ash deposits as have occurred in the distant past on the Earth, Moon, Mars, Venus, Mercury.
- Many questions about lava emplacement processes and effects can be answered through temporal coverage with sufficiently high spatial resolution.

Effusion rate comparisons – contemporary eruptions



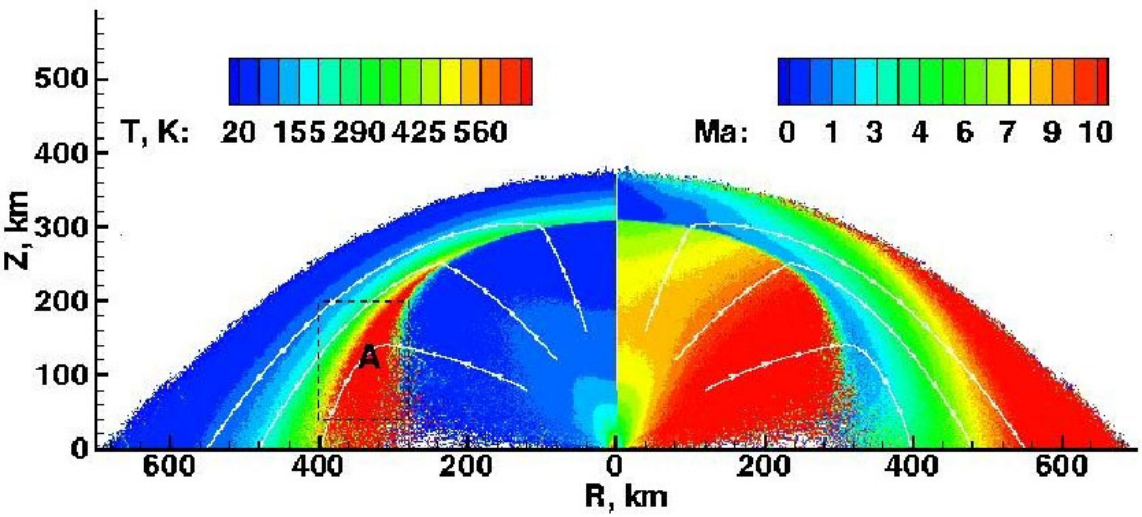
COMPOUND FLOW FIELD
(Amirani)



New lava covered ~ 620 km^2 in less than five months. Kilauea covered only ~10 km^2 in the same time.

Plumes: key questions

- Why different types of plumes when lavas are presumably same composition?
- Where are the vents? Links to subsurface not known (to what extent do near-surface volatiles drive explosivity?)
- What is the "dust"? What is the relative role of condensation (SO_2,S_x) as plumes expand and cool vs lofting of ash particles?
- How do plume materials escape? Volcanic material escapes (ions in torus, dust in magnetosphere) but simulations of plumes indicate material contained by canopy shocks (pulses or temporal variations?)



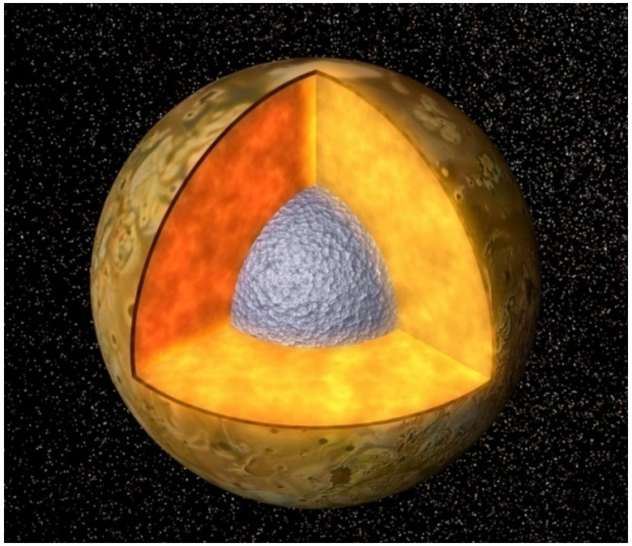
Model of an isolated Pele-type plume. Contours of temperature and Mach number are shown (Zhang et al., 2003)

Science Goals: Interior structure

NOSSE Goal 2. Determine Io's interior structure, e.g., whether it has a magma ocean, and implications for the coupled orbital-thermal evolution of Io and Europa.

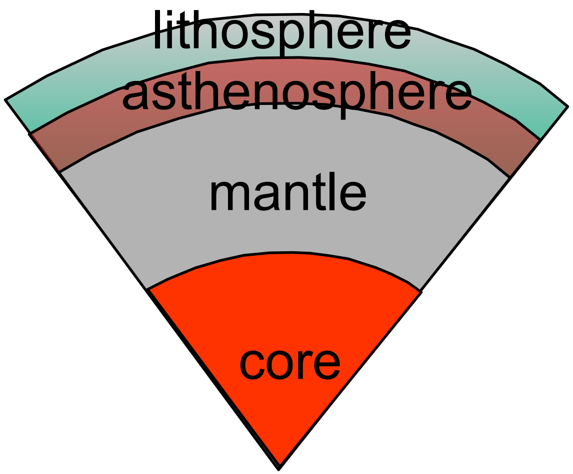
Magma oceans shaped the early Earth, Moon, Mars and may be present on exoplanets. If the magma ocean is confirmed on Io, it will be the only body in the solar system where we can study one today.

V&V Objective A2: Determine the state (melt fraction) of Io's mantle



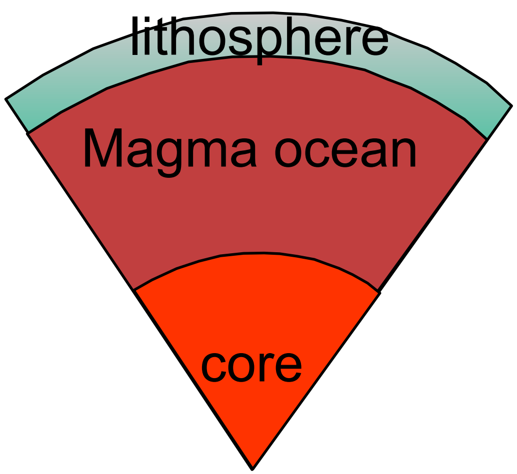
What's Happening Inside Io?

Io's bulk density (3.53 g cm^{-3}) and moment of inertia indicate that it has a large core and silicate mantle, and the tall mountains suggest the lithosphere is >20 km thick, but the state of Io's mantle, where the lavas originate, is poorly known.



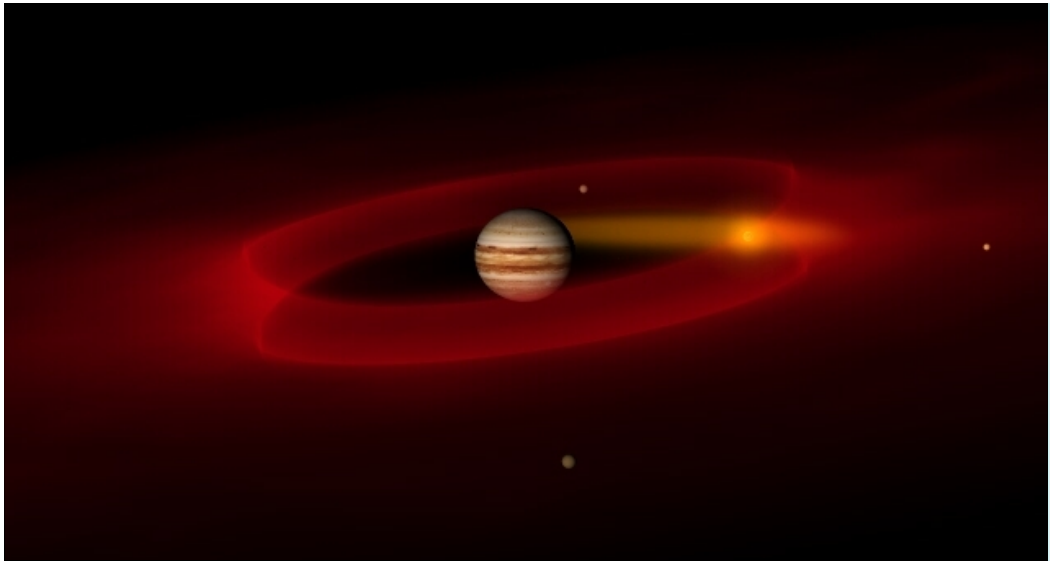
How much partial melting and how is it distributed? Is there a magma ocean?

Model 1. Earth-like interior structure with a partially molten asthenosphere (~20% melt) over a solid mantle.



Model 2. Unique interior structure with a mushy (crystal-rich) magma ocean; core not convecting (no internal magnetic field) due to hot mantle.

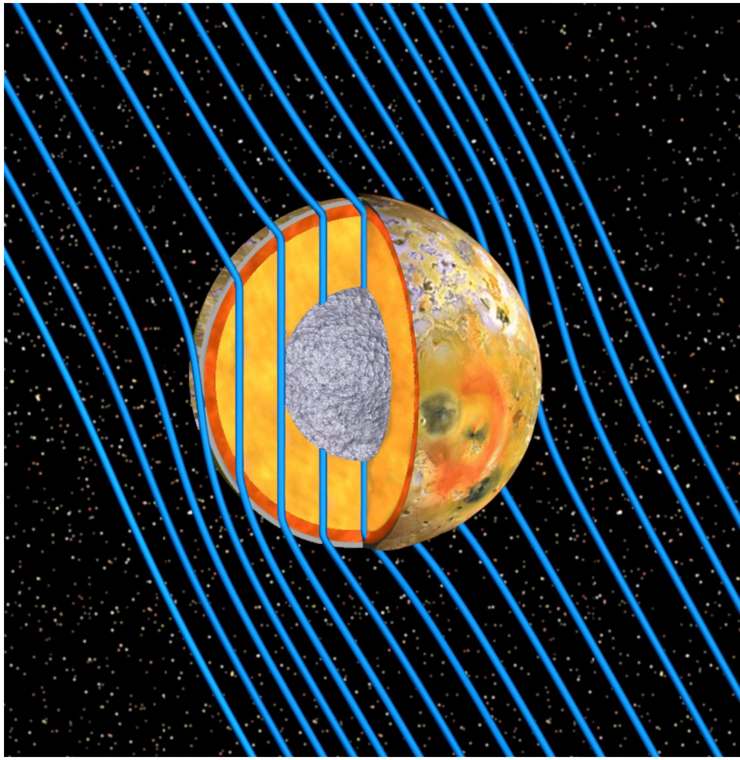
Magnetic fields and their implications for Io's interior



- Galileo measurements showed no intrinsic magnetic field for Io
- Tilt of Jupiter's magnetic field relative to the planet's rotation axis causes a variable field at Io
- Detected perturbations to Jupiter's magnetic field at Io could be due to:
  1. A conducting layer in Io's interior (Khurana et al., 2011)
  2. Plasma environment (Roth, 2012)
  3. Io's atmosphere (Bloecker et al., 2016)

Khurana et al: suggested magma ocean from Galileo data

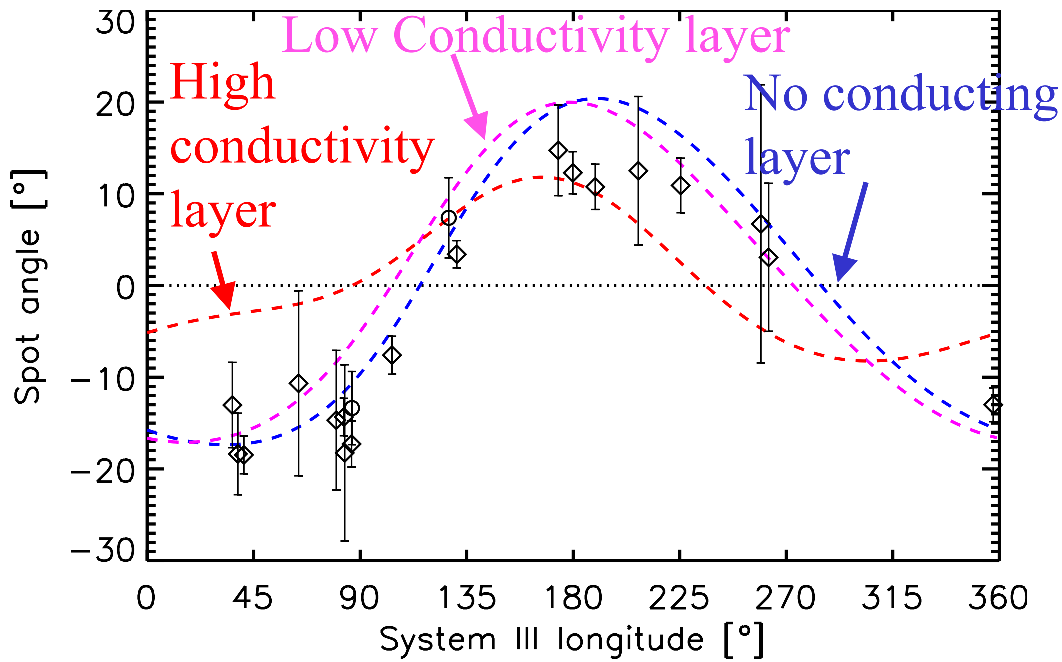
- High lava temperatures hinted at an underlying mushy magma ocean (Kezthelyi et al., 1999)
- Magnetic field measurements from Galileo imply magma "ocean" – no intrinsic magnetic field, but an induced one (Khurana et al., 2011) consistent with a silicate magma ocean ~50 km below surface



Khurana et al., 2011:
Io's magma ocean has high electrical conductivity, it deflects the varying (as Io rotates) magnetic field from Jupiter, shielding the inside from disturbances

HST observations (Roth, 2012)

- The conducting layer inferred by Khurana et al. (2011) should affect the time-variable morphology of Io's aurora
- HST observations can be explained **without** a high-conductivity layer
- Other recent work suggests global asymmetries in Io's atmosphere could explain "significant parts" of the magnetic field perturbations measured by Galileo (Bloecker et al., 2016)



Angle between the line connecting the two auroral spots and Io's equator v. system longitude. Observations are compared to the magnetic field with no ocean (blue dashed line) and an ocean with d = h = 50 km and conductivities of 0.05 S m^{-1} (pink dashed line) and 0.43 S m^{-1} (red dashed line). The latter is most similar to Khurana et al. (2011).

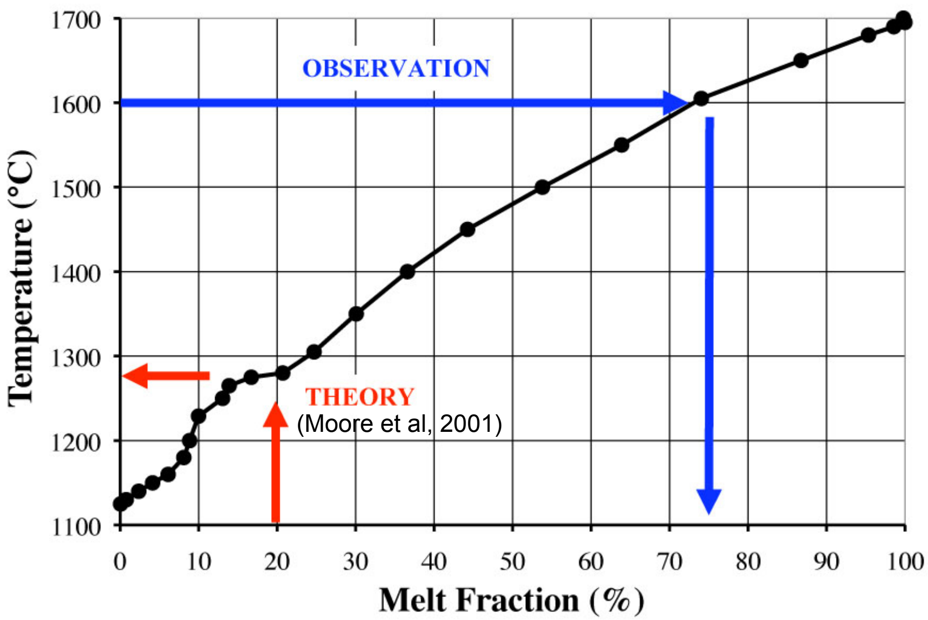
Gravity Science can constrain mantle/lithosphere rigidity

- Measurement of tidal Love number Re(k2)
  - Constrain mantle/lithosphere rigidity x thickness from measuring tides near periapsis and apoapsis.
  - By combining Re(k2) with lithospheric thickness from magnetic induction and topographic flexture measurements, we can constrain mantle rigidity
  - Mantle rigidity sensitive to melt fraction

Bierson and Nimmo (2016) made a prediction of the tidal Love number Re(*k*2). This value can be measured by spacecraft and used to determine if Io has a magma ocean

Measurements of magma temperature

- High lava temperature measurement by Galileo hinted at primitive, low viscosity lava (ultramafic) and higher melt fraction, implying an underlying mushy magma ocean (Kezthelyi et al., 1999)
- But Galileo data was saturated, had a poor SNR, and limited coverage. Galileo instruments not designed to measure high T lavas
- High spatial resolution measurements of fresh lavas could constrain composition
- Measurements of lavas flowing in tubes (skylights) could provide evidence of high temperatures (Davies et al., 2016)



Keszthelyi et al. (2007):
Melting curve for the top of Io's mantle
- higher melt fraction than predicted

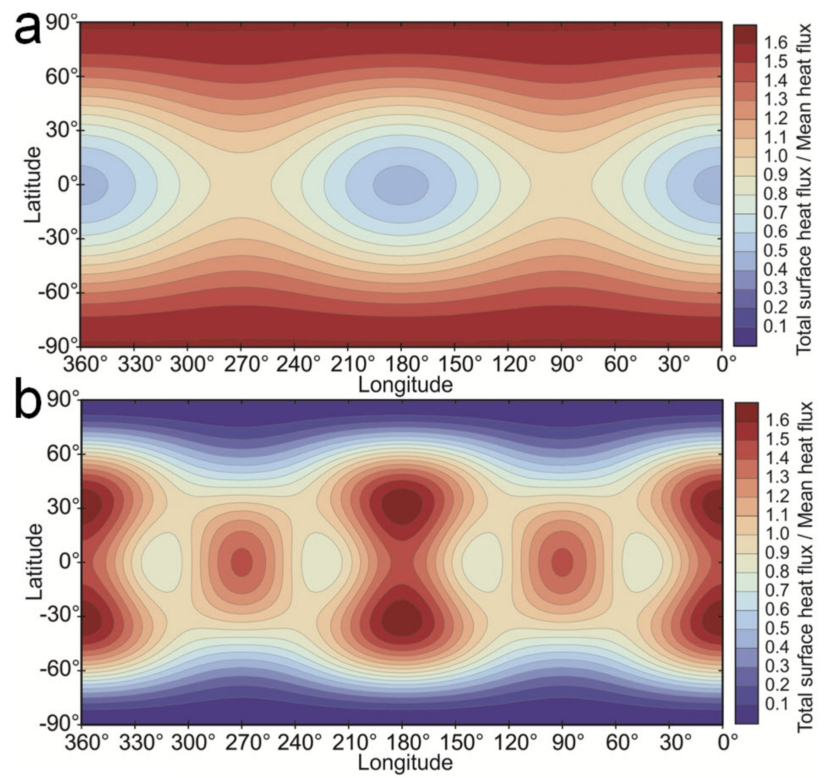
Existence of ultramafic lavas have implications for early volcanism on Earth and terrestrial planets

Science Goals: Tidal heating

NOSSE Goal 3. Determine the magnitude, spatial distribution, temporal variability, and dissipation mechanisms of Io's tidal heating.

Tidal heating driving Io's activity controls the Jovian system's habitable zone and understanding it gives insight into potential habitable environments in extrasolar planetary systems

V&V goal A3: Test and revise models of tidal heating mechanisms



Deep mantle vs asthenosphere dissipation models after Ross et al. (1990). From Hamilton et al. (2012)

Heat Flow

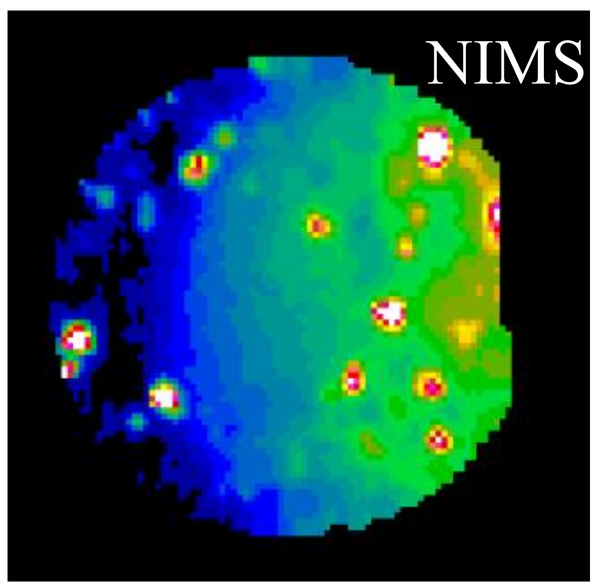
- Io's surface heat flow can be estimated from observations of its thermal emission. Hot spots account for most of the heat flow (easily measured) but low T emission from cooling lava flows also significant and difficult to separate from passive solar heating

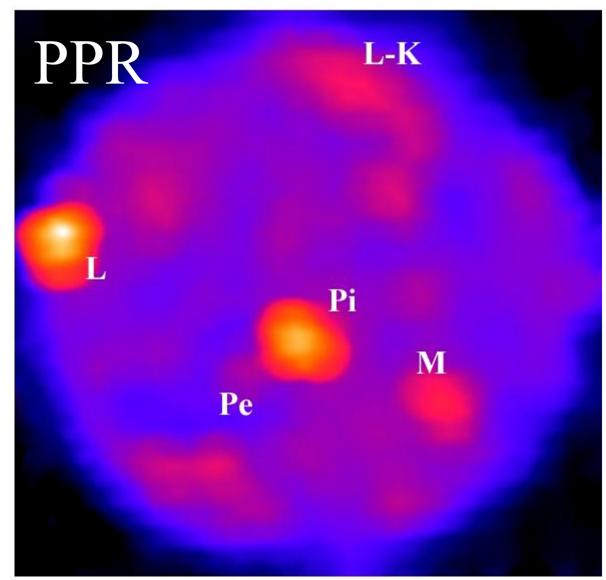
- Spatial and temporal measurements of heat flow distribution and its variability would provide constraints for interior circulation, how Io's orbit is evolving, and for tidal dissipation and relation to Europa's tidal heating

- Galileo estimate (PPR): 2 W m^{-2} (Spencer et al., 2000; Rathbun et al., 2004): night time temperatures drop less than expected at high latitudes, implying excess endogenic emission at high latitudes (cooling lava flows?)

Other estimates of global heat flow:

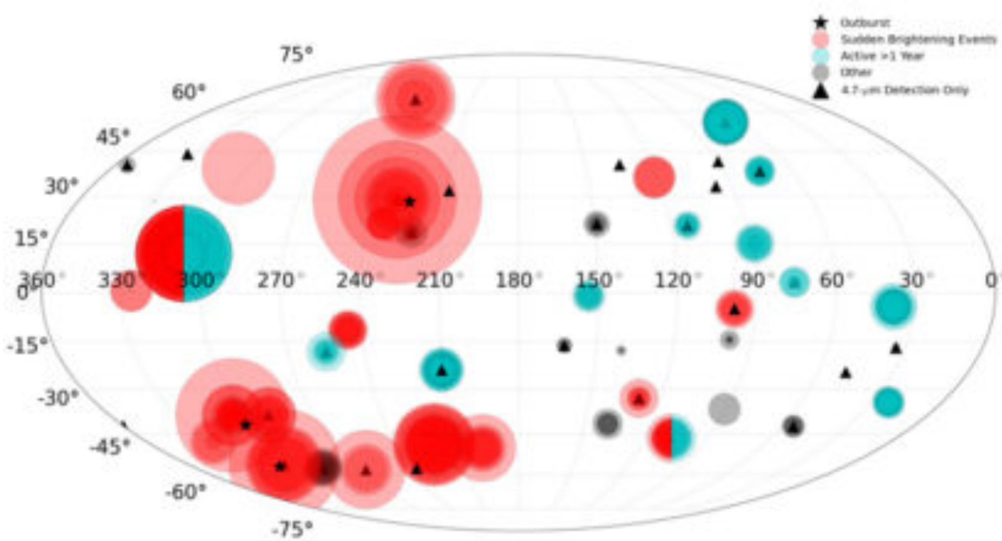
3±1 W m^{-2} (Veeder et al., 2004)
2.1±0.7 W m^{-2} (McEwen et al., 2004)
0.6-1.6 x 10^{14} W total



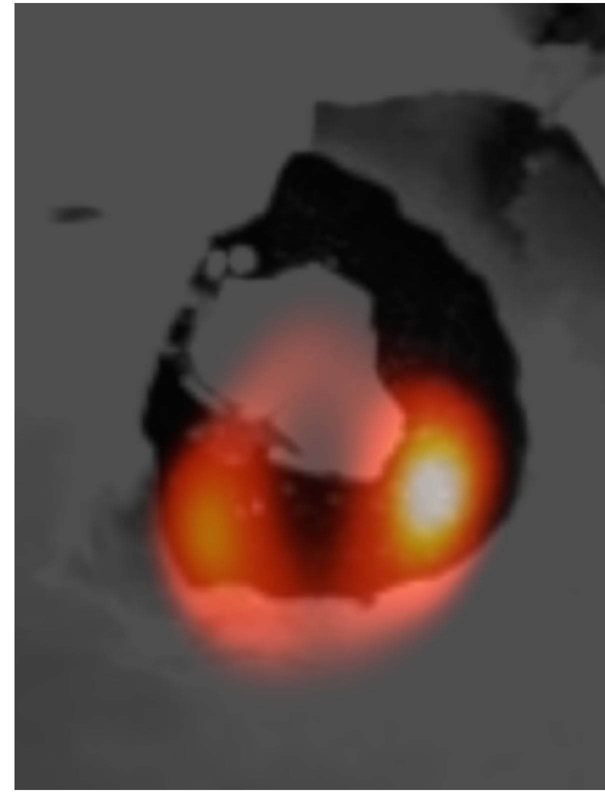


Ground-based observations have improved but have limited coverage

- Resolution has improved (see LBT image)
- Observing cadence has improved, using Keck, IRTF, and Gemini – partly for support of Juno and EXCEED
- **But polar heat flow is key**



Hot spots detected from August 2013 through December 2015, displayed on a full map of Io and illustrating the approximate length of time they were visible. The size of the circle corresponds logarithmically to the intensity. Loki Patera is at 310 West longitude, 10 North latitude and Kurdalagon Patera is at 220 West longitude, 50 South latitude. (Credit: Katherine de Kleer and Imke de Pater, UC Berkeley)



The LBT image of Loki Patera (orange) laid over a Voyager image of the volcanic depression. The emission (in orange color) appears spread out in the north-south direction due to the telescope point-spread function; it is mainly localized to the southern corners of the lake. (Image: LBTO- NASA, Michael Skrutskie)

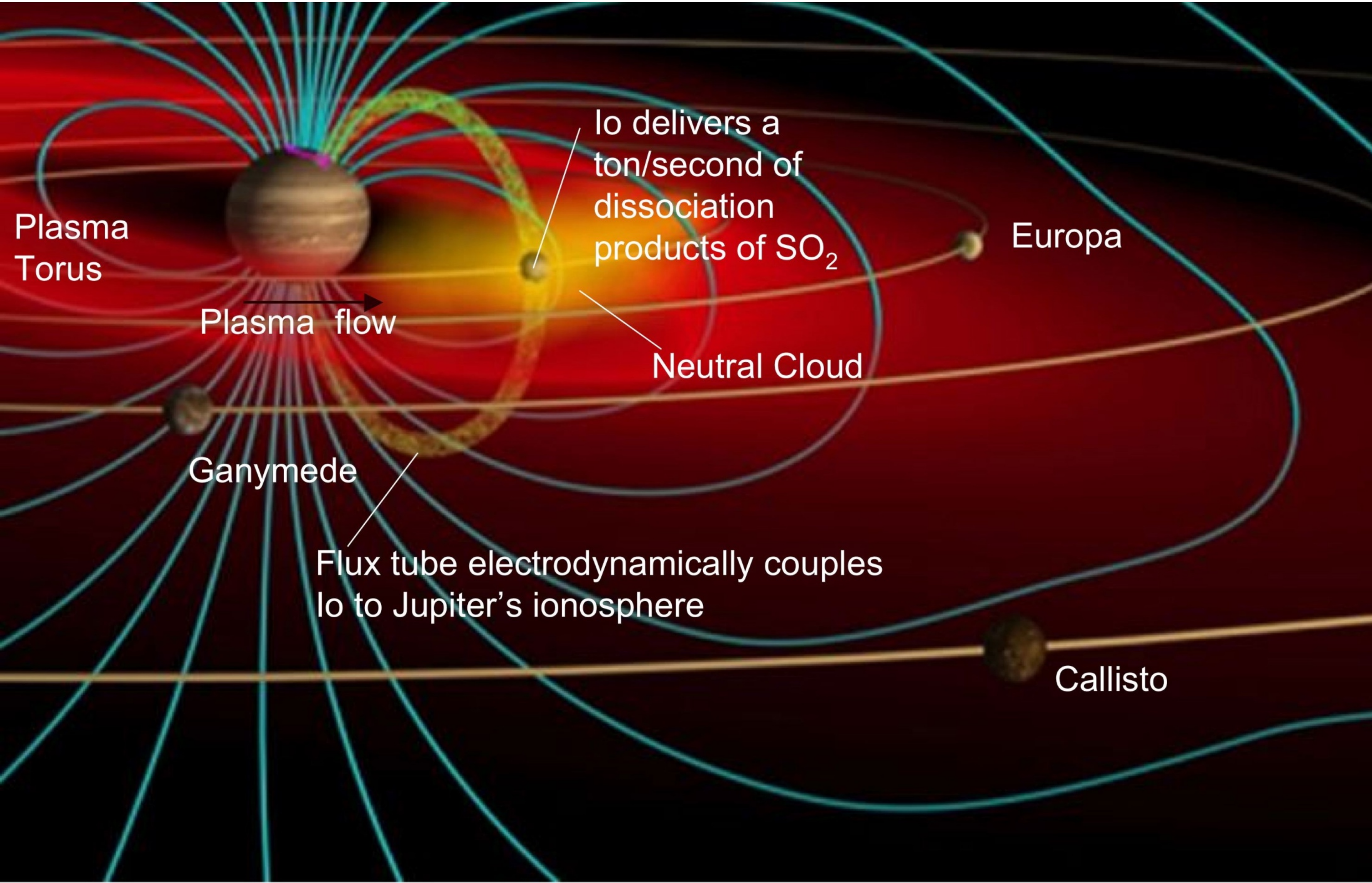
Io V&V Primary Objectives (Turtle et al.)

A1. Test and revise models for active volcanic processes on Io.
A2. Determine the state (melt fraction) of Io's mantle.
A3. Test and revise models of tidal heating mechanisms.

- Secondary Objectives

B1. Test and revise models for tectonic processes on Io.
B2. Test and revise models for the interrelated volcanic, atmospheric, plasma-torus, and magnetospheric mass- and energy-exchange processes.
B3. Test and revise models for the state of Io's core via tighter constraints on whether Io is generating a magnetic field.
B4. Improve our understanding of endogenic and exogenic processes controlling Io's surface composition.
B5. Improve our understanding of Jupiter system science.

Influence of Io's volcanism in the Jovian system



Summary

- Still many unknowns about Io's interior, composition, tidal heating/dissipation
- Tidal heating is key for understanding ocean worlds and habitability (highly relevant to exoplanets)
- Extreme volcanic processes on Io provide a window into the early Earth, other planets, and some exoplanets
- Io science goals remain valid but state-of-the-art updates are needed on how they can best be addressed
- Measurement requirements might be achieved by complementary observations (e.g. small sats)
- Pre-Decadal study is needed to define how objectives can be achieved by an Io-dedicated mission and other available remote sensing resources