



Io After the Galileo Spacecraft: Results and unanswered questions

Rosaly Lopes

Jet Propulsion Laboratory

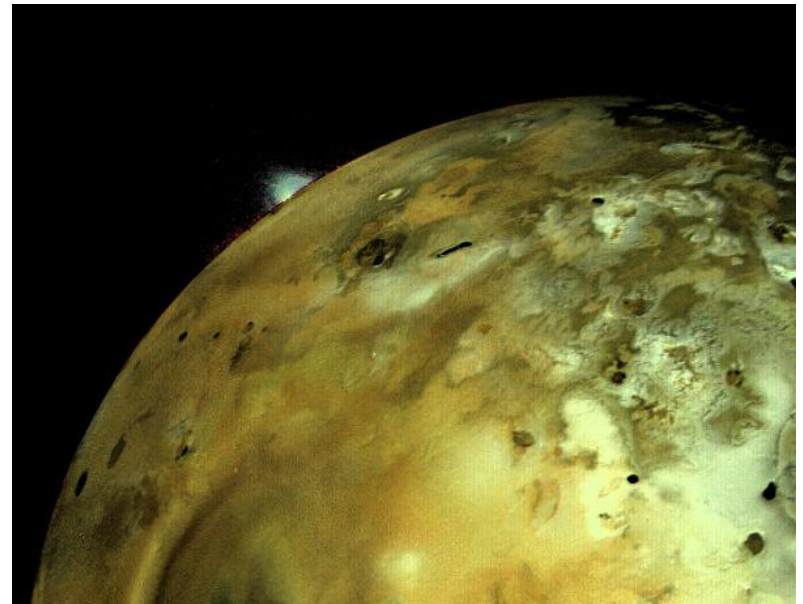
Discovery of Active Volcanism on Io: Voyager results

Discovery of Pele and Loki plumes (Morabito et al., 1979)



Peale et al (1979): Laplace resonance created significant forced eccentricity in the orbits of Io and Europa, so these bodies would be deformed periodically, leading to significant internal heating. Predicted that Io could have active volcanoes!

- Nine plumes detected
- Thermal emission (IRIS) found to coincide with location of a plume, SO₂ detected in Loki plume (Hanel et al., 1979)



Not a single impact crater...

Voyager results and some questions:

What is surface composition?

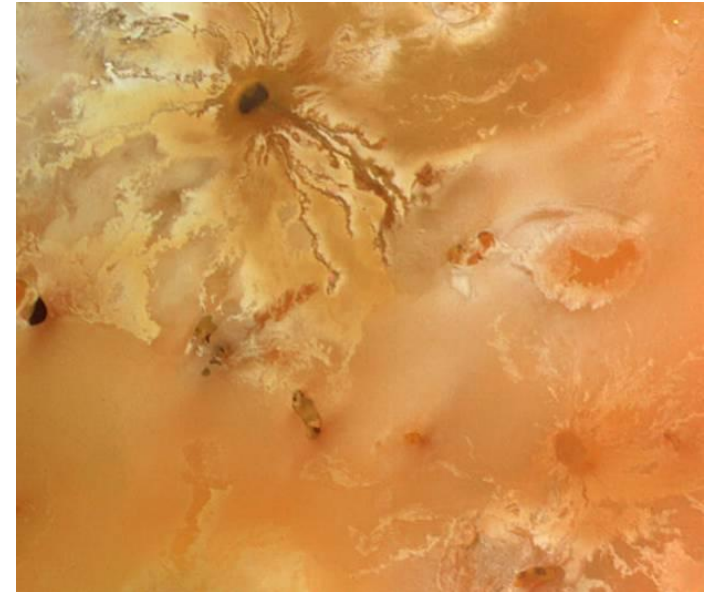
- SO₂ frost identified (asymmetrically distributed, almost absent 250-323°W)
- Post-Voyager consensus was sulfur and SO₂ frost surface composition but topography produced by silicate materials

Sulfur or silicate volcanism?

- Melting temperature for sulfur (~400 K) lower than melting temperature for basaltic lavas (1300-1450K) but temperatures measured by Voyager consistent with either
- Longer wavelength channels on NIMS added to measure temperatures at Io

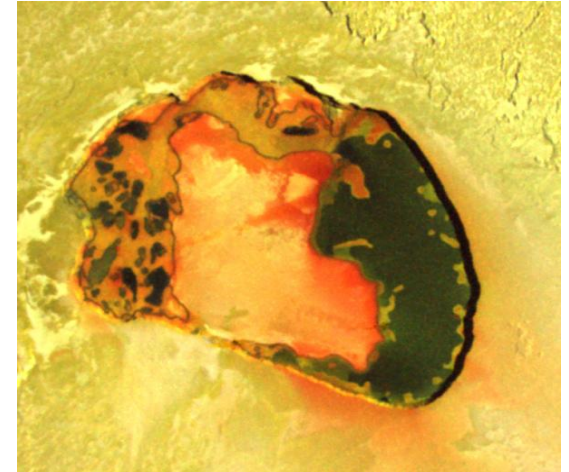
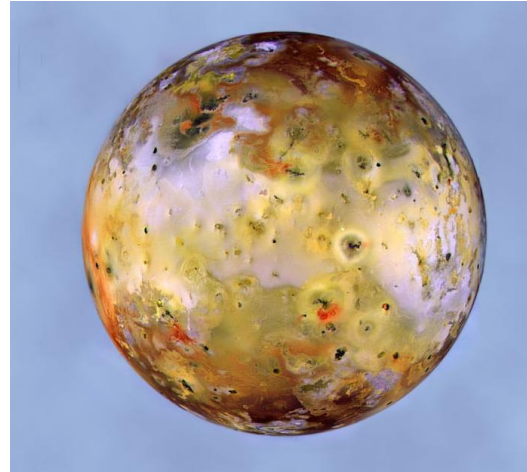
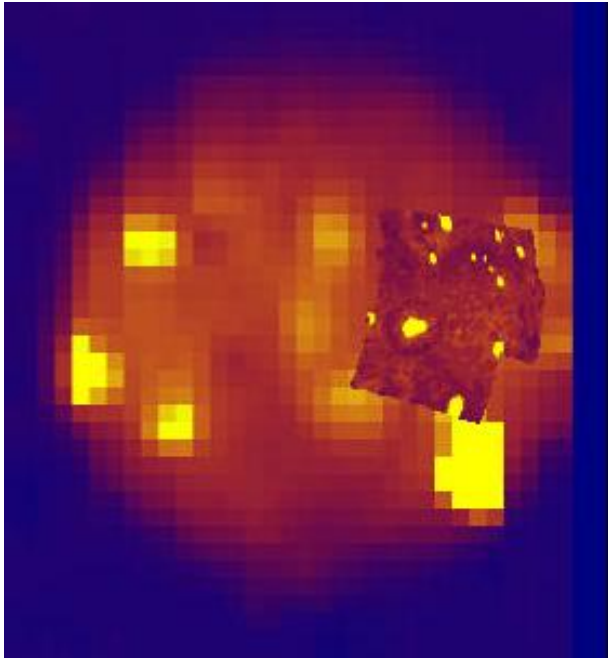
Evidence of SO₂ atmosphere, patchy in distribution

- Volcanic or sublimation origin?



Sagan (1979) proposed sulfur volcanism at Ra Patera
Carr and Clow (1980) argued that topography could not be produced by sulfur

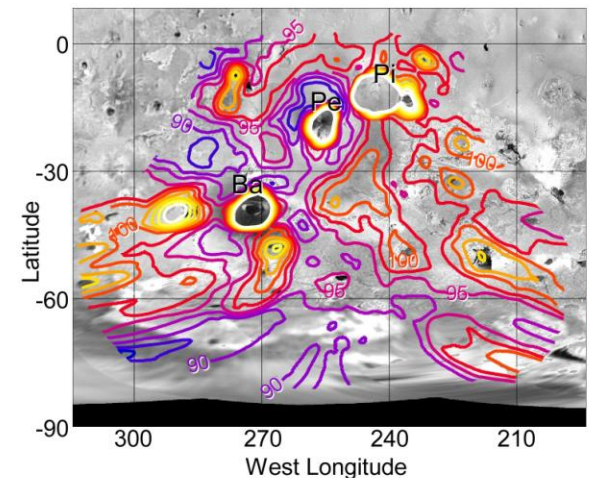
The Galileo Era: 1995-2003



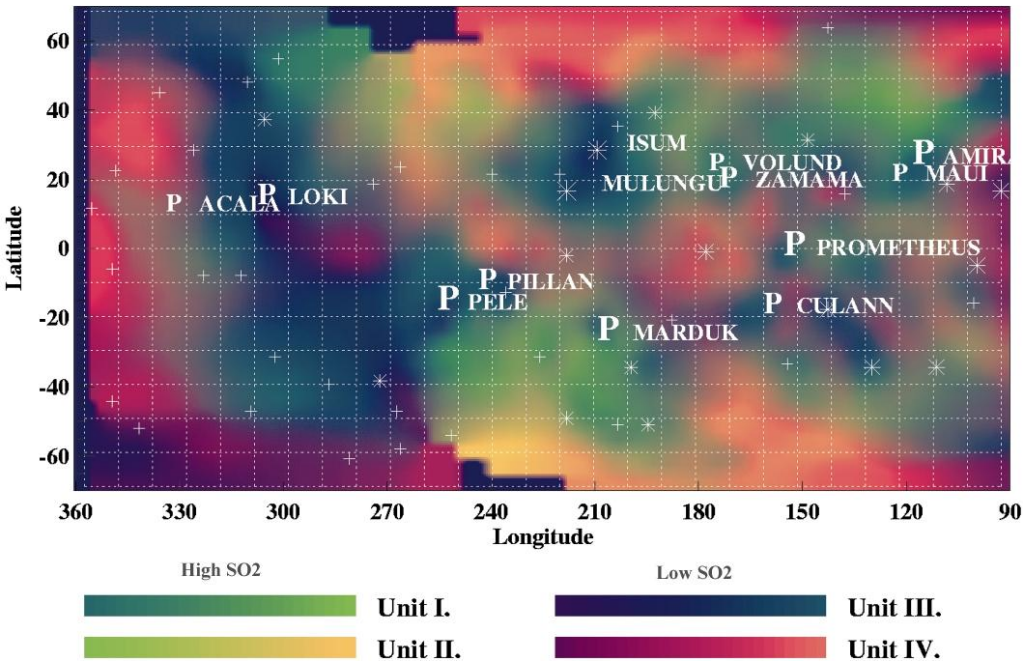
SSI: surface mapping, topography, detected plumes, surface changes, high temperature measurements and detection of hot spots (1 μm when Io in eclipse)

NIMS (1-5.2 μm) measured temperatures, mapped distribution and granularity of SO_2 and distribution of hot spots, detected 71 unknown hot spots, detected broad 1 μm absorption and 3.15 μm band

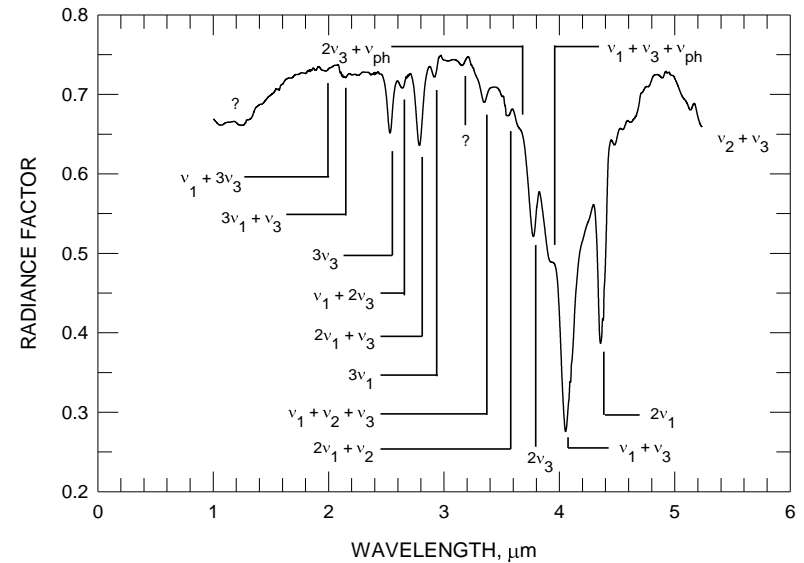
PPR: constraints on heat flow, temperature maps, detected unknown hot spots (radiometer: visible-100 μm)



Composition: Mapping distribution of SO₂ frost on surface using NIMS: SO₂ cycle, correlation with volcanic activity, plumes



Plume (P) are sources of fine grained frost (I)
 Unit II: Metamorphosed SO₂ snowfields
 Units III, IV: SO₂ poor regions
 * (long lived hot spots), + (hot spots)

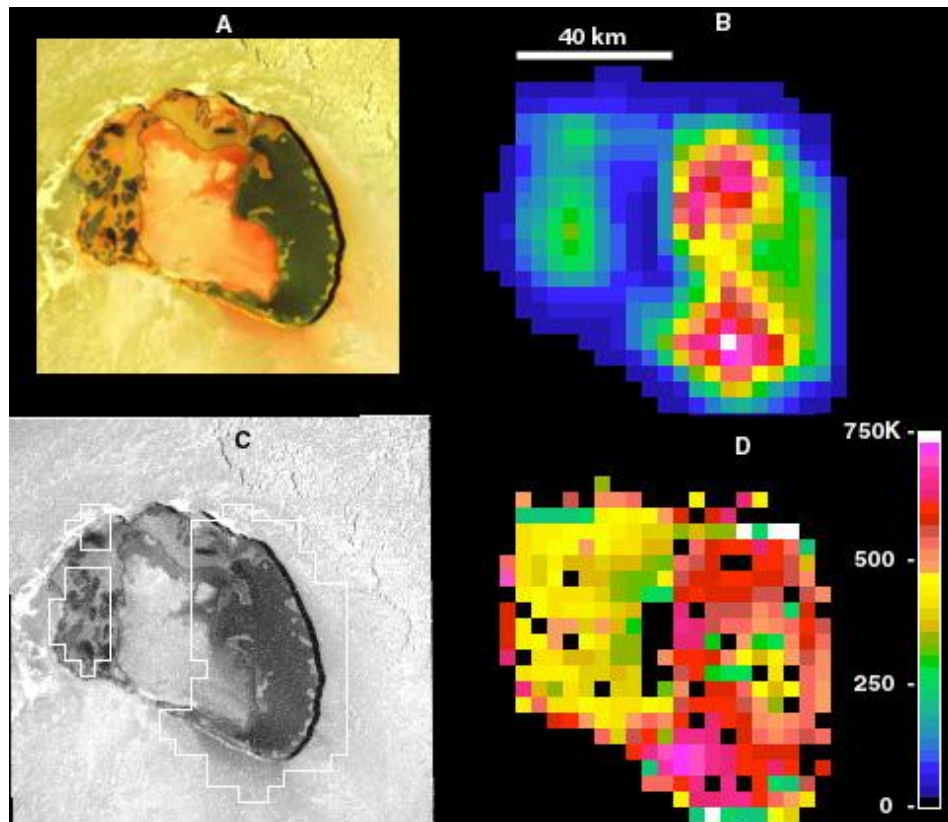
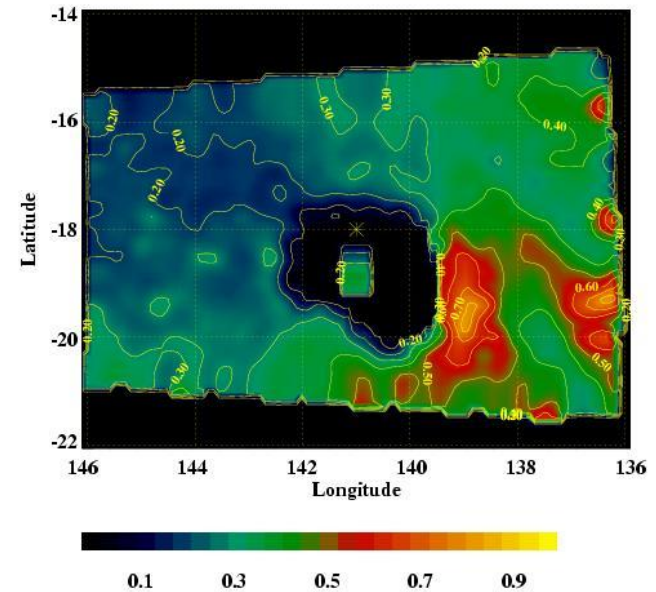
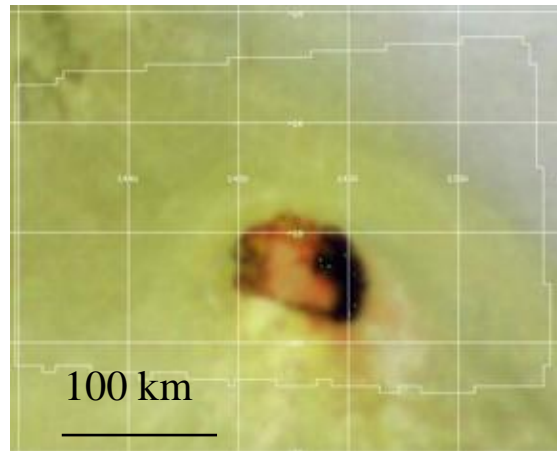


3.15 μm band (H₂O in SO₂, mineralic OH, HCl?)

1-1.6 μm broad absorption: Fe-containing salts, feldspars, FeS₂, sulfur with impurities?

SO₂ present nearly everywhere, larger grain sizes near equator, plumes transport SO₂ to mid latitudes (Carlson et al., 1997, Douté et al., 2001)

Tupan: Local distribution of SO₂ (Douté et al. , 2003) and temperatures (Lopes et al., 2004)



SO₂ frost coverage map (8 km/pixel) from 0 (black) to 1 (yellow). More coverage on E side (greater activity)

High resolution (135 m/pixel) image (A)
4.7 μm NIMS map, 8 km/pixel (B)
NIMS projection on SSI (C)
Temperature map (D)

Io's Surface composition: some unanswered questions

- What is the composition of the surface?

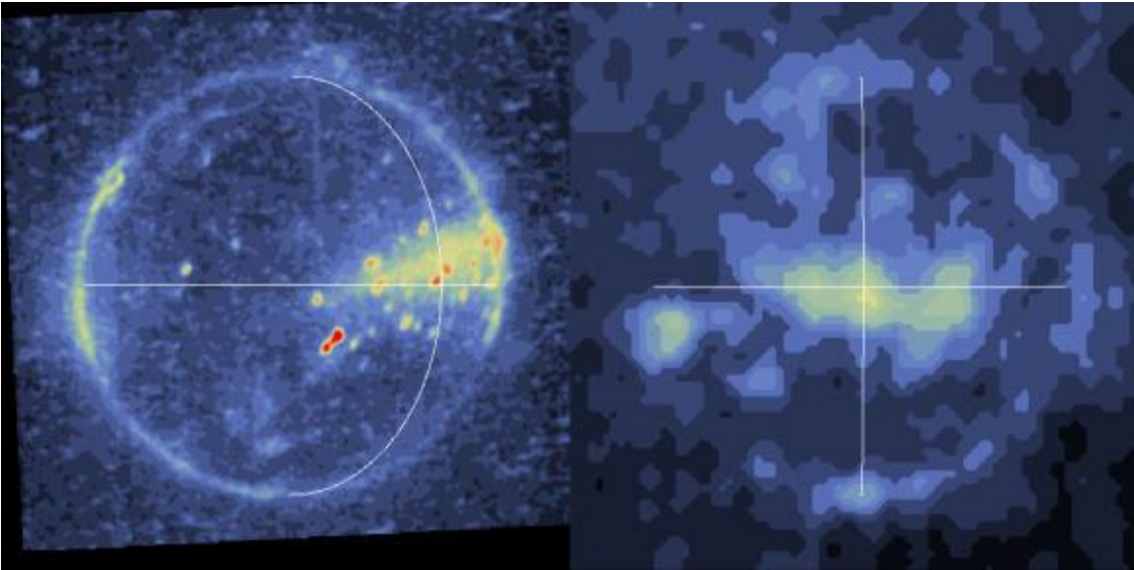
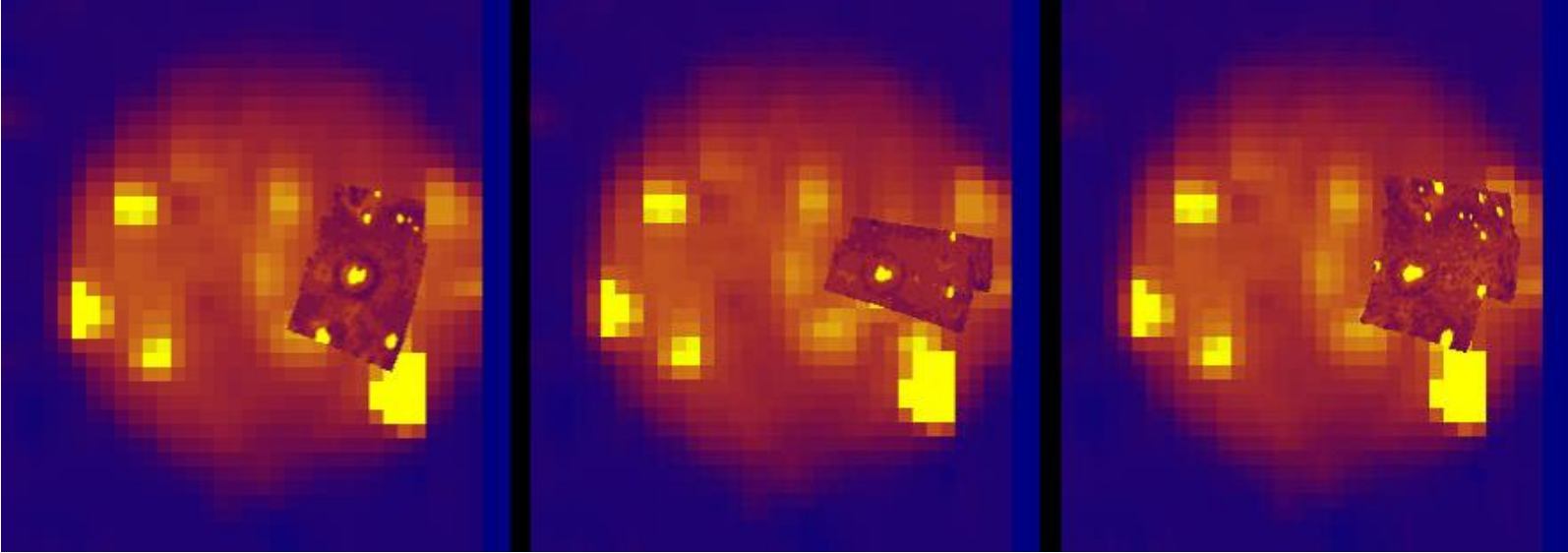
SO₂ frost ubiquitous, obscures a lot of the surface
S and SO₂ in plume deposits

Relationship between colors and composition not well understood

Minor constituents not yet identified

Composition of lavas not well constrained

Active volcanism: Thermal mapping by NIMS and SSI



NIMS thermal mapping
(4.7 μm , 250 km/pixel
and 50-75 km/pixel)

SSI imaging of Io in
eclipse (1 μm)

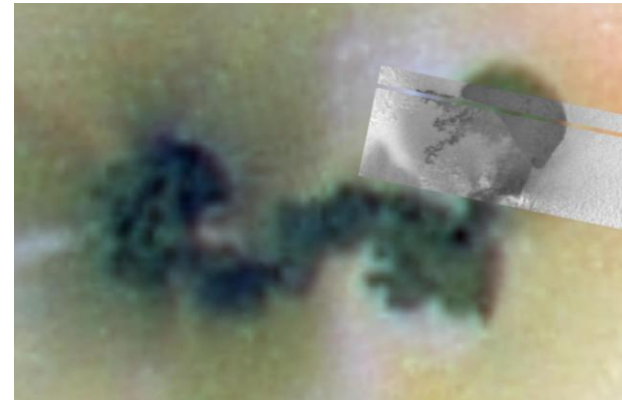
Volcanic eruption styles on Io

(Williams and Howell, 2007)

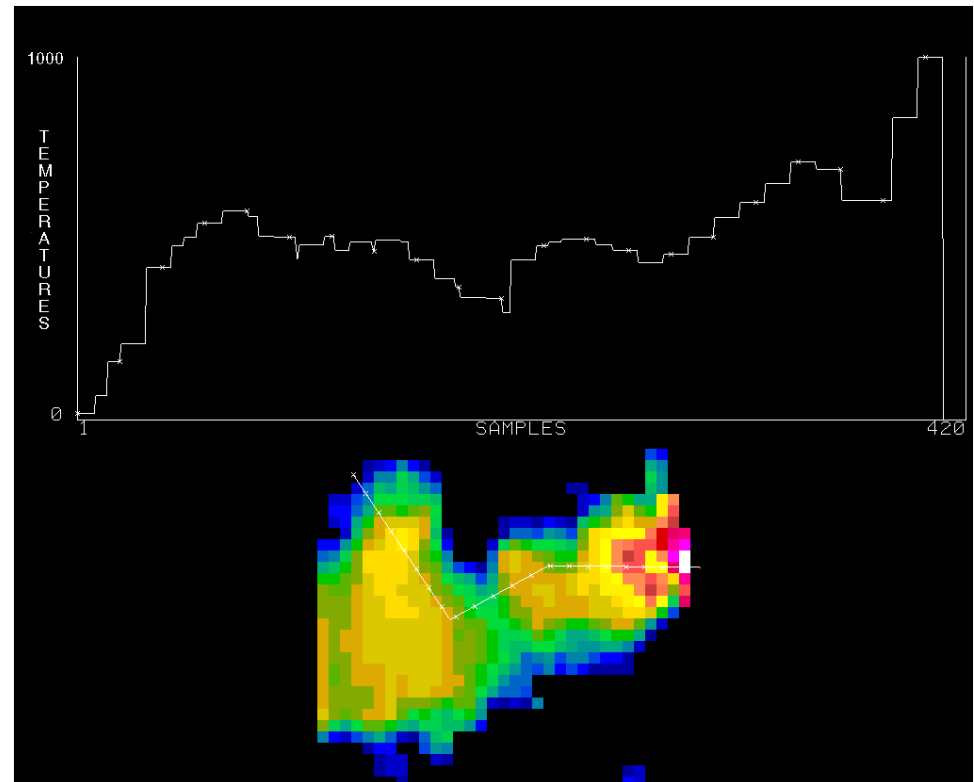
- Flow-dominated (Promethean) eruptions (lava flows, smaller plumes)
- Explosion-dominated (Pillanian) eruptions (violent, large plumes, fire fountains)
- Intra-patera (Lava lakes, flows confined within paterae)
- Unnamed (short duration, weak events, possibly sulfur flows)
- Unidentified (possibly cryovolcanic, SO₂ flows)

Flow-dominated (Promethean)

Persistent activity, relatively small plumes (< 200 km) associated with long-lived lava flows. Plumes migrate, and shut off after flow stops.

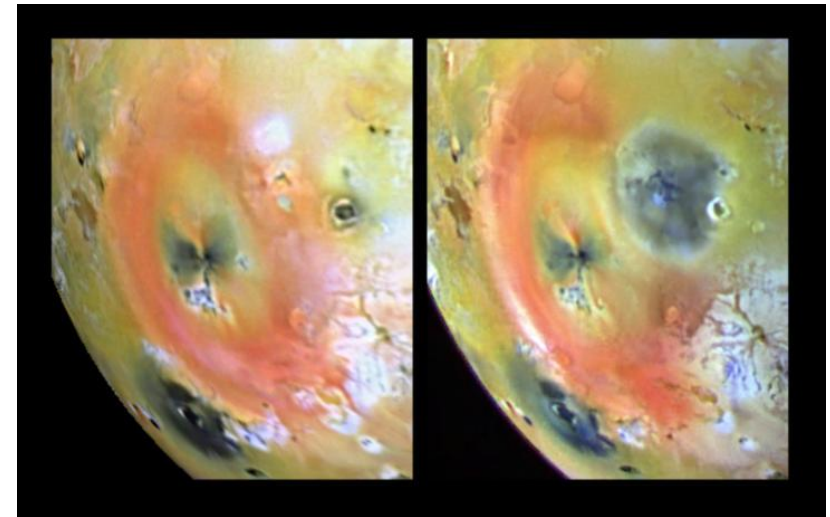


NIMS mapping of lava flow showed hottest area near caldera (Voyager-era plume vent)



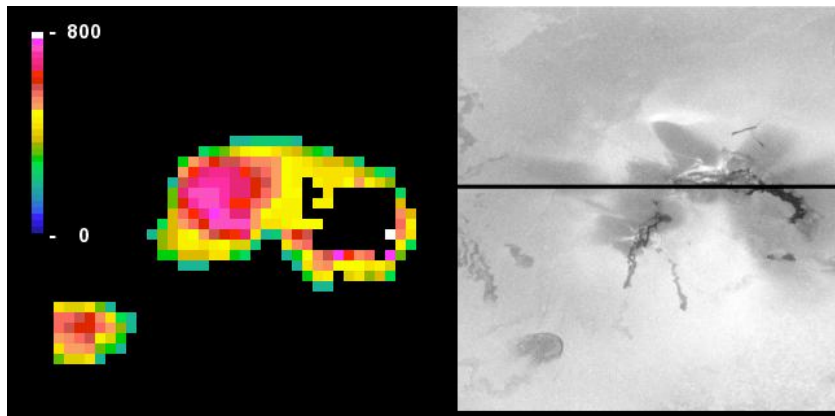
Explosion-dominated (Pillanian)

Short-lived intense episode showing high temperatures, fissure-fed, fire fountains, extensive pyroclastic deposits, tall intermittent plumes (> 200 km). High temperatures (> 1500K, perhaps > 1800K) detected

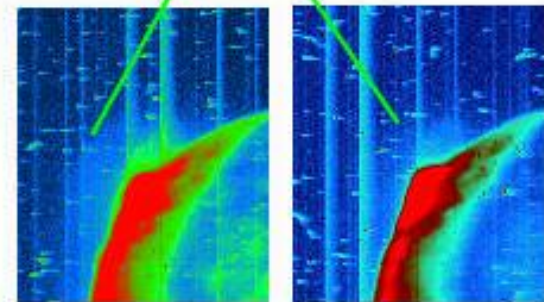


April 1997

Sept 1997



500-km high plume
from new eruptive center

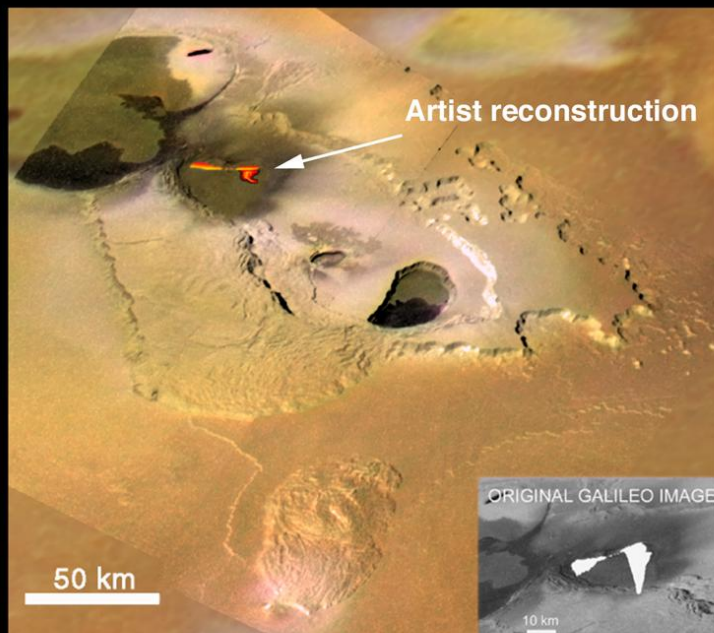


NIMS detected a new hot spot (Thor) in 2001. Thor was source of 500 km high plume. NIMS high res observation showed saturated region, SSI showed flows.

Pillanian eruption at Tvashtar

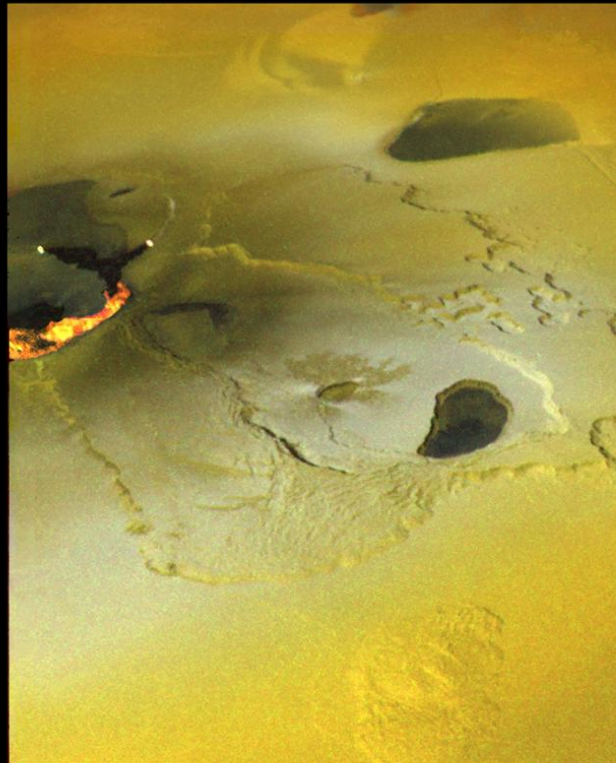
Eruption Styles at Tvashtar Catena, Io 60°N, 120°W

November, 1999:
~1.5 km tall lava fountains
Dark pyroclastics & flows
 $T \geq 1230^\circ\text{C}$



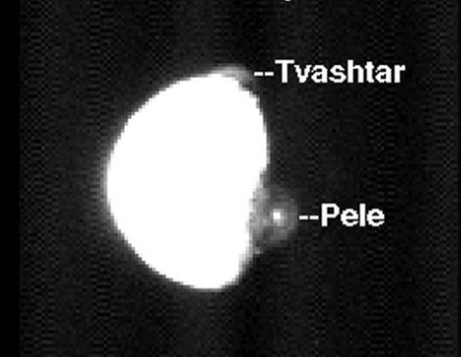
I25ISGIANTS01 (185 m/px)
merged w/C21 color (1.4 km/px)

February, 2000:
Hot lava lake or flows
 $T \sim 1260^\circ\text{C}$

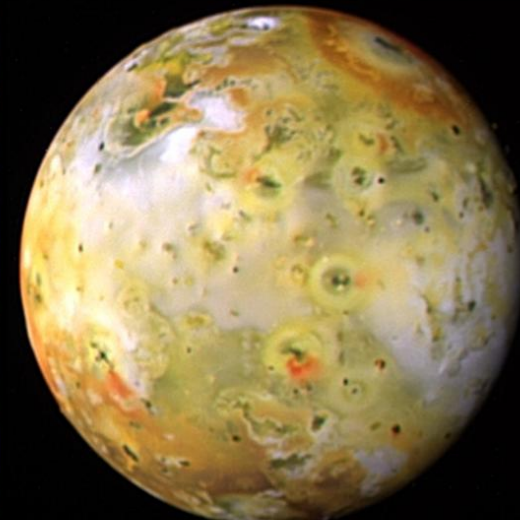


I27ISTVASHT01 (400 m/px)
merged w/C21 color (1.4 km/px)

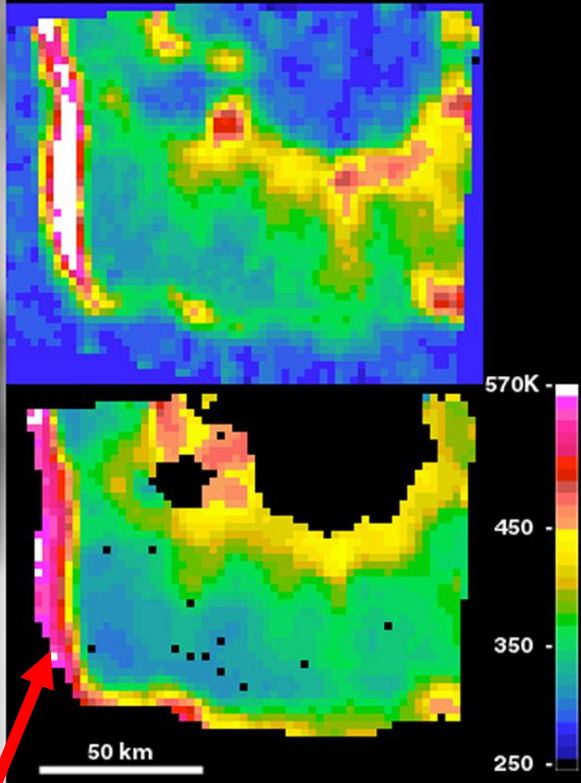
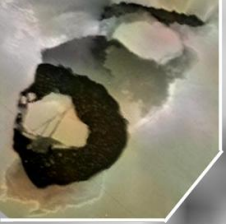
Cassini: December, 2000
400 km tall plume



December, 2000:
1400 km diameter
ring of red sulfur pyroclastics

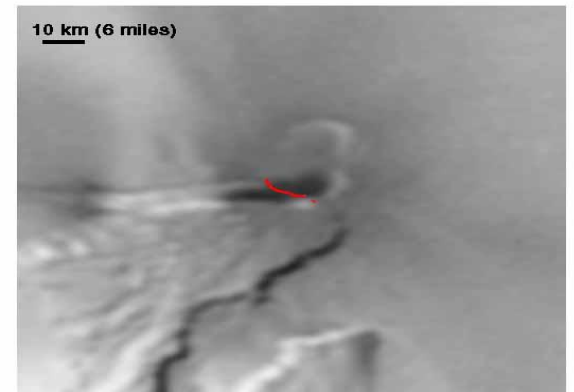
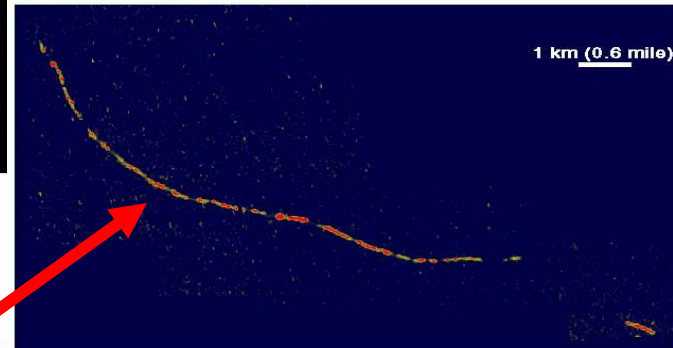


G29ISGLOCOL02
10.2 km/px



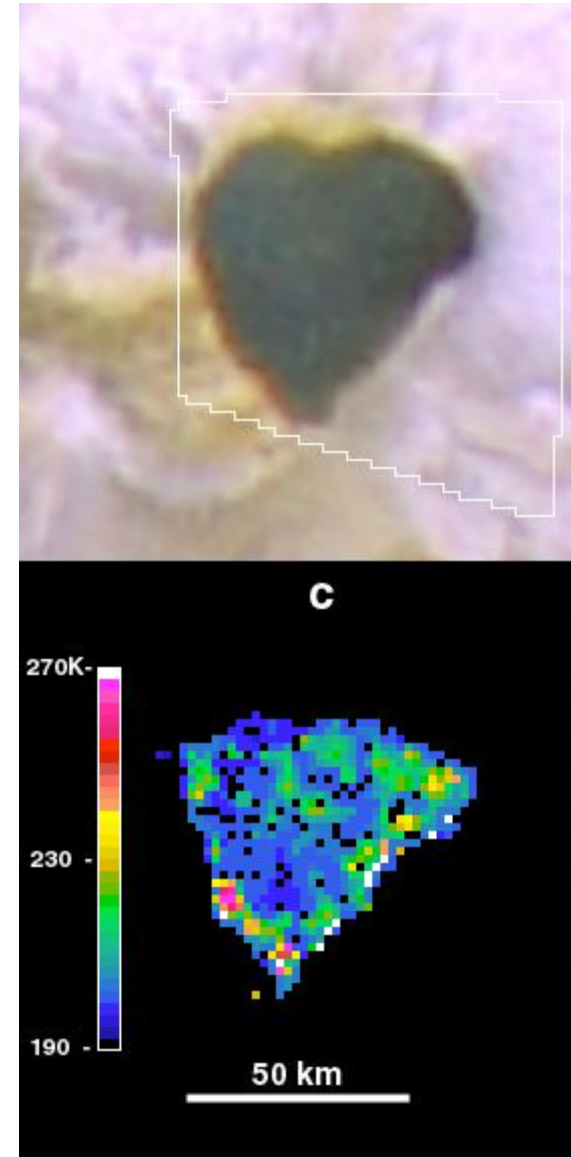
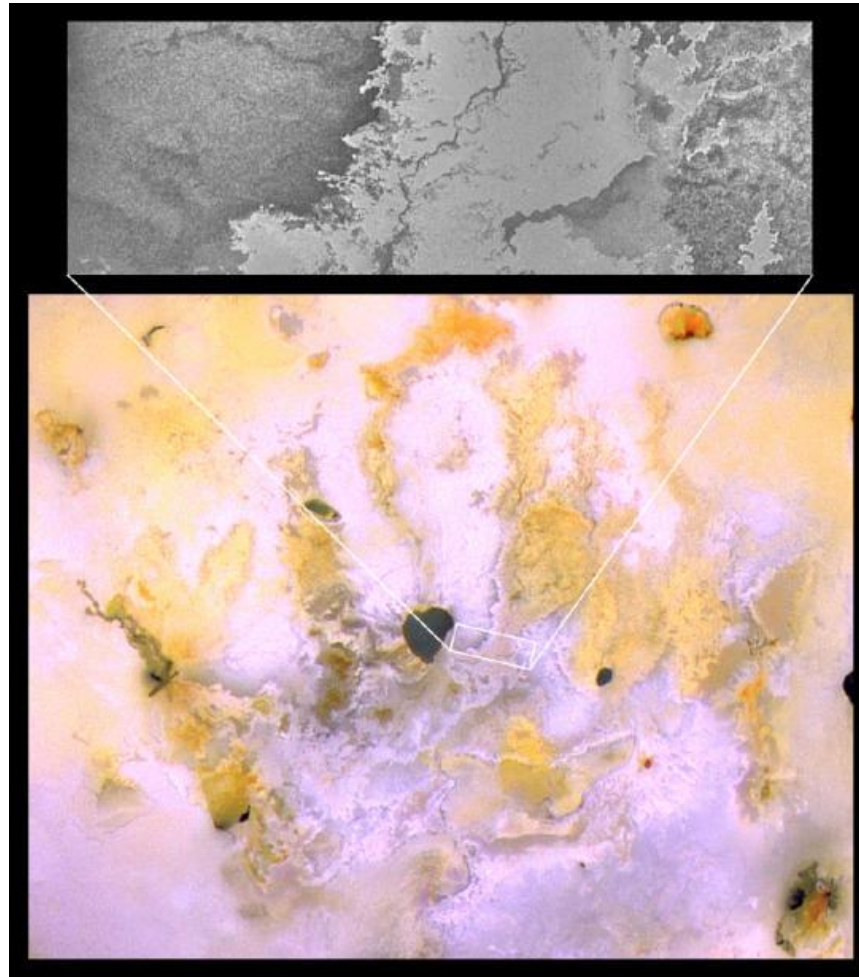
Intra-patera volcanism:

**NIMS observation of
Loki and SSI
observation of Pele
show hot edges at
paterae**



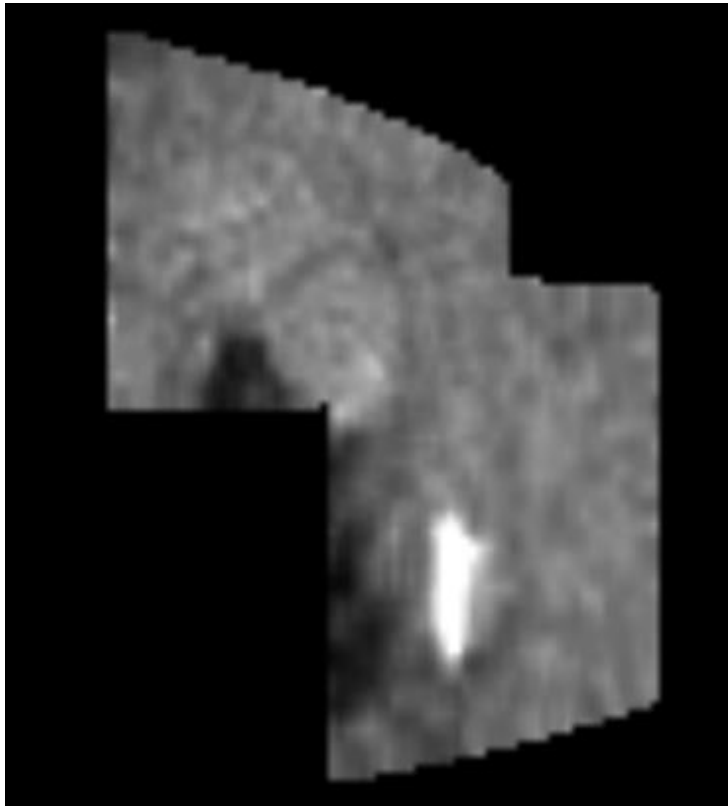
Unnamed style of activity: short duration,
weak events, possibly sulfur flows

Emakong
Patera:
possible sulfur
flows
(Williams et
al., 2001)
SSI images
and NIMS
thermal map
(Lopes et al.,
2004)



Unidentified style of activity: possible SO₂ flow in Balder

SO₂ rich area inside Baldur caldera, topographically confined. Possible low temperature eruption of SO₂. Gas escapes upward, liquid + solid confined topographically, forming slush.



NIMS (4.1 μm /continuum ratio map)
1 km/NIMS pixel



Chaac and Balder calderas, SSI image
(image is ~ 100 km across)

Io's volcanism: some unanswered questions

- How does volcanism operate in Io's extreme environment?

Low gravity, lack of plate tectonics, high magma temperatures (superheating?), constant activity

- What is the composition range of magmas?

Ultramafic, superheated?

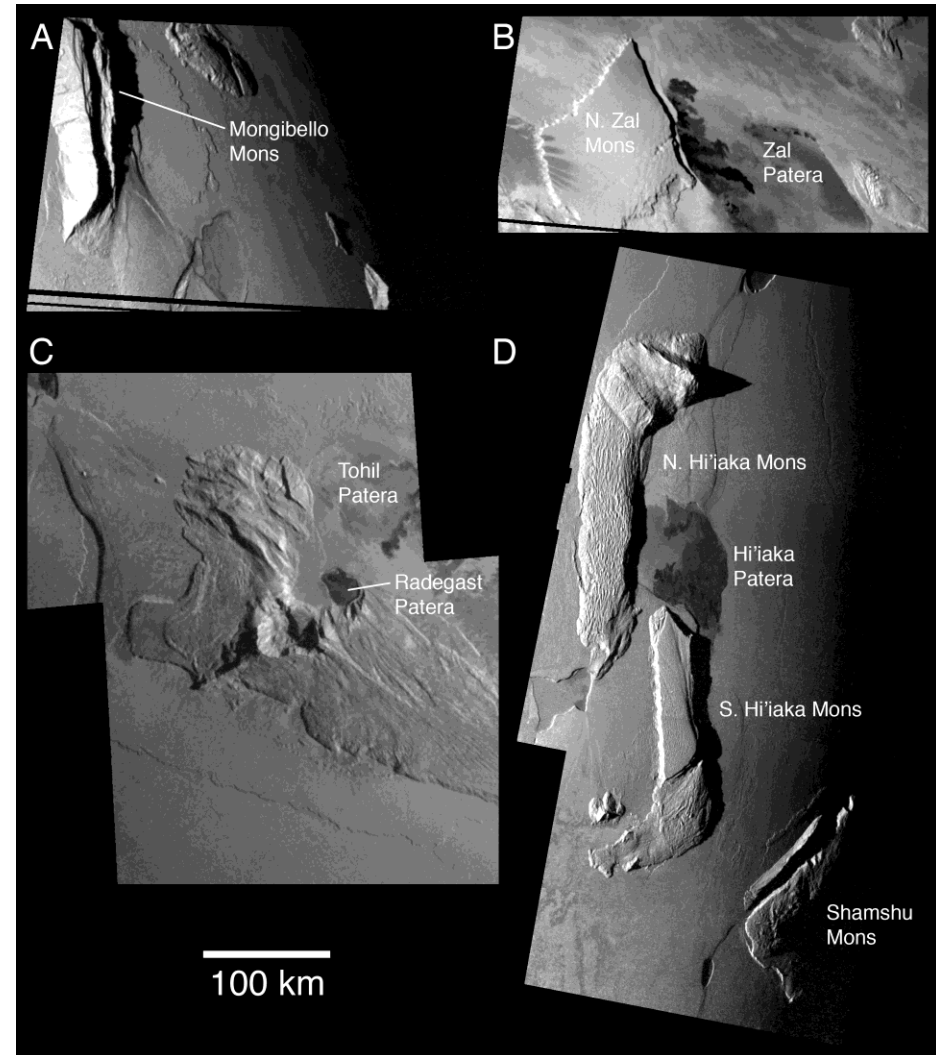
- How do Io's very large volcanoes work?

Most common type is patera.

- Does sulfur volcanism exist? SO_2 volcanism?

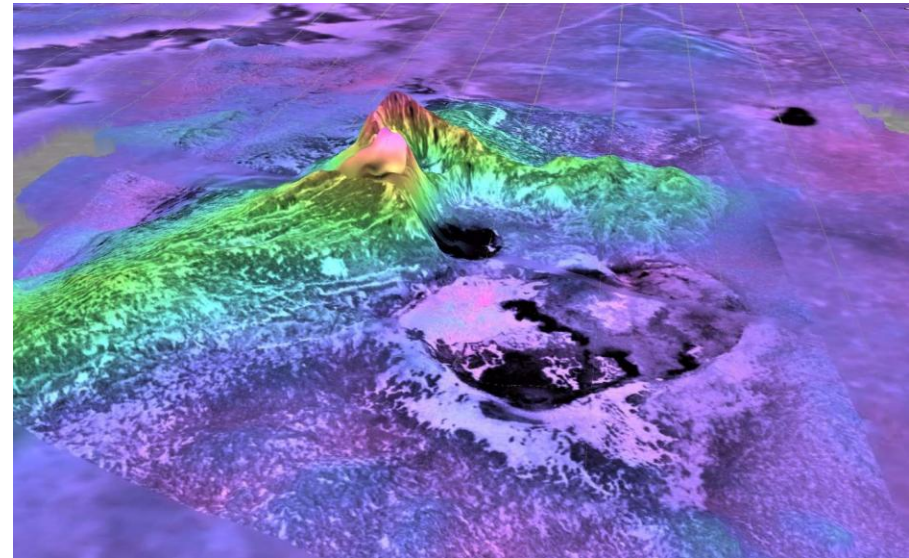
Mountains and Tectonics

- Defined as > 1 km above surrounding terrain, ~ 135 known to date (Turtle et al., 2007)
- Max height 17.5 km at Boösaule Montes (Schenk et al., 2001)
- Most appear to be tectonic: uplifted, sometimes tilted blocks, bounded by steep scarps
- $\sim 41\%$ appear associated with paterae, but generally mountains are anti-correlation with hot spots
- No obvious tectonic pattern except for bimodal variation with longitude (moderate enhancements in number density $\sim 25^{\circ}\text{N}$, 65°W and 20°S , 265°W ; Schenk et al., 2001)



Mountains and Tectonics: origin

- Mountains not volcanoes, why?
- Schenk and Bulmer (1998) proposed that rapid resurfacing rate ($\sim 1 \text{ cm yr}^{-1}$) drives rapid subsidence (current surface could be buried to a depth of 10 km in 10^6 years)
- Subsidence caused by volcanism can induce compressive stresses in lithosphere, driving mountains up by extensive thrust faulting
- Faults may act as conduits for magma (some mountains associated with paterae)



Perspective view of Tohil Mons and patera. Topography derived from stereo analysis (P. Schenk). Vertical exaggeration $\sim 25x$. Amphitheater crest $\sim 8 \text{ km}$ high.

Io's Surface: more unanswered questions

- What is the relationship between mountains and paterae?

What is relationship between resurfacing rate and tectonics?

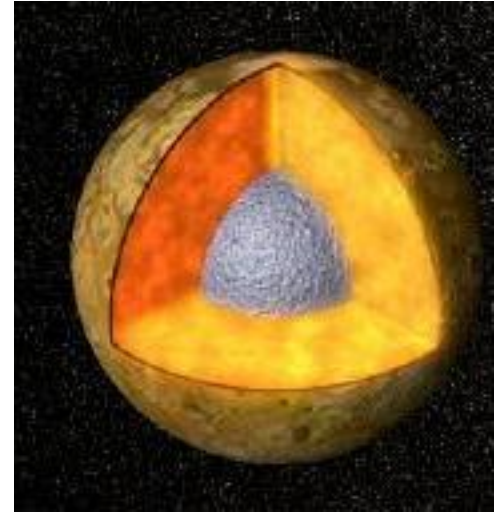
- Resurfacing rate

What is causing resurfacing and what is the rate?

What is the major contributing process?

What is the relative contribution of flows, dust, SO₂?

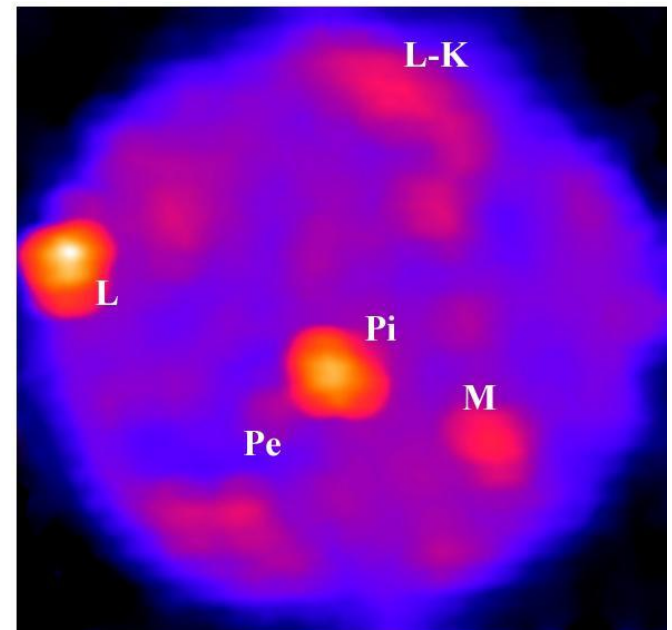
Interior



- Mass, radius, density known from Voyager and Pioneer.
- Density ($3,527.8 \text{ kg m}^{-3}$) implied large iron core
- Galileo data improved accuracy of measurements of Io's mass and radius and determined Io's quadrupole gravitational coefficients
- Io is a 2-layer body consisting of a metallic core and silicate mantle.
- Radius of core is 0.37 to 0.52, depending on its composition (Fe or FeS)
- Galileo measurements showed no intrinsic magnetic field
- Volcanic activity suggests Io had differentiated a global crustal layer and a partially molten asthenosphere
- Strong lithosphere required to support observed topography (mountains)

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
- Previous estimates of average heat flow:
 - Veeder et al., 1994 (ground based): $> 2.5 \text{ W m}^{-2}$
 - McEwen et al., 1996 (Voyager): $> 1.85 \text{ W m}^{-2}$
- Galileo estimate (PPR night time emission, Spencer et al., 2000; Rathbun et al., 2004): 2 W m^{-2}
- PPR: low latitude night time temperatures drop less than expected at high latitudes, implying excess endogenic emission at high latitudes (cooling lava flows?)
- Latest estimates (combined data):
 - $3 \pm 1 \text{ W m}^{-2}$ (Veeder et al., 2004)
 - $2.1 \pm 0.7 \text{ W m}^{-2}$ (McEwen et al., 2004)
 - $0.6\text{-}1.6 \times 10^{14} \text{ W}$ total



Interior structure: some unanswered questions

- **What is the composition of the core?**

Io is differentiated, with large metallic core (0.37-0.52 Io radius) and a silicate mantle

Composition and origin uncertain

No magnetic field detected

Physical state of core not known, likely liquid due to intensely heated mantle above

- **What is the thickness of the lithosphere?**

Estimates model-dependant (a few km to 100 km; Schubert et al., 2004), may not be homogeneous. Origin of mountains still unclear.

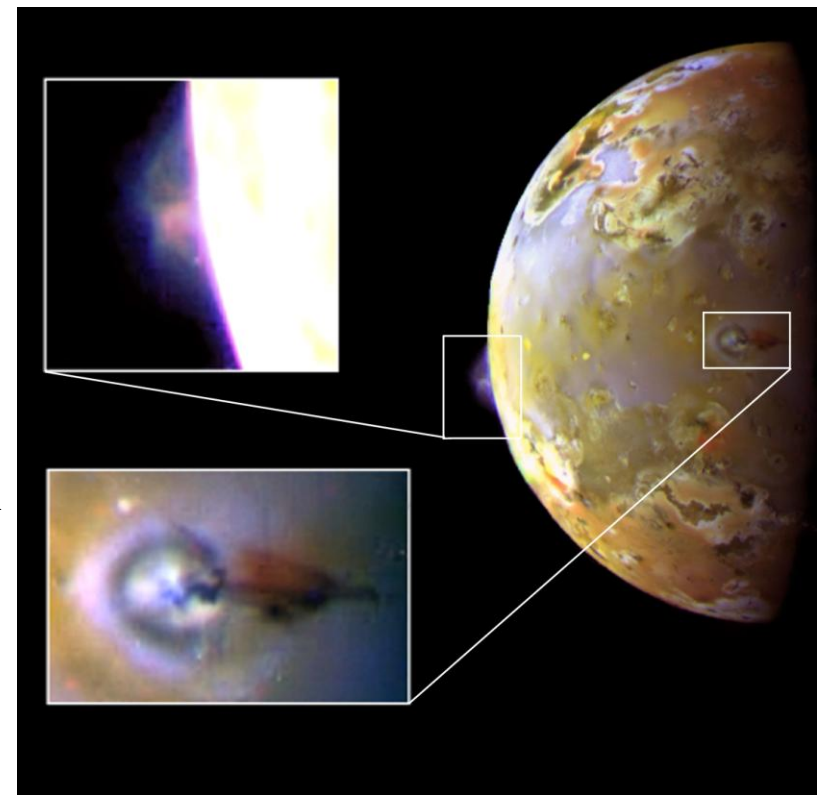
- **What is the total heat flow?**

Various estimates, but all model dependent Polar regions are surprisingly warm – different style of volcanism? (Rathbun et al., 2004)

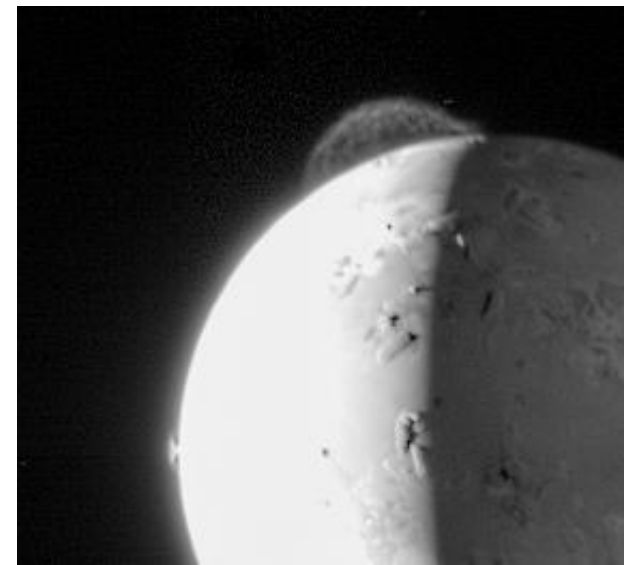
Better estimates require models of (or data for) dawn, dusk, and polar emission

Accurate measurement of heat flow and its variability would provide constraints for interior, how Io's orbit is evolving, and for tidal dissipation and relation to Europa's tidal heating

- **Plumes** observed from 16 volcanic centers, others inferred from deposits
- Smaller (~100 km) SO₂ and dust plumes associated with lava flows (Prometheus, Masubi): plume created when hot lavas bury icy, SO₂ rich substrate (Kieffer et al., 2000).
- Giant S rich plumes (Pele, Tvashtar, Pillan) reach 100s of km, rarer, fainter, variable. Produced by primary gases from paterae and lava lakes
- Stealth plumes (Johnson et al., 1995): Acala, Culann: dust-free, gas seen in eclipse images



- Atmosphere is unique in apparent spatial and temporary variability, link to volcanism
- Latest models indicate widespread SO₂ atmosphere (not “patchy”), but with horizontal variations in pressure (Lellouch et al., 2007)
- Modest local density enhancements over active plumes at low to mid latitudes



Plumes and atmosphere: some unanswered questions

- Why two main types of plumes when lavas are presumably same composition?

Are all small plumes generated Prometheus-style?

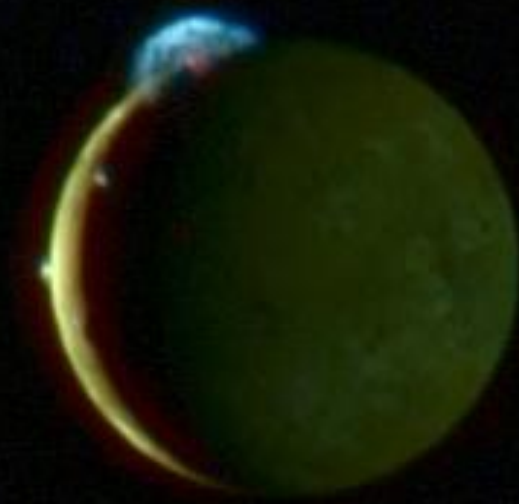
- Where are the vents? Links to subsurface not known
- What is the “dust”? What is the relative role of condensation (SO_2, S_x) as plumes expand and cool vs lofting of ash particles?
- How do plume materials escape? Volcanic material escapes (ions in torus, dust in magnetosphere) but simulations of plumes indicate material contained by canopy shocks (pulses or temporal variations?)
- Plasma transport and formation of torus

We still don't understand how variations in volcanic activity control supply of plasma to the torus, the mechanism of dust formation, and many other details of how matter and energy flows between Io, Jupiter, and the magnetospheric plasma

- Characterization of the atmosphere

Full atmospheric model explaining role of sublimation of Sun-warmed volatiles vs volcanic venting not yet available.

After Galileo: observations from spacecraft



Io and Europa from New Horizons (LORRI and MVIC): March 2007

NH detected surface change, several plumes (showed filamentary structure at Tvashtar, detected a new hot, temperatures consistent with basalt.