# Io Volcano Observer


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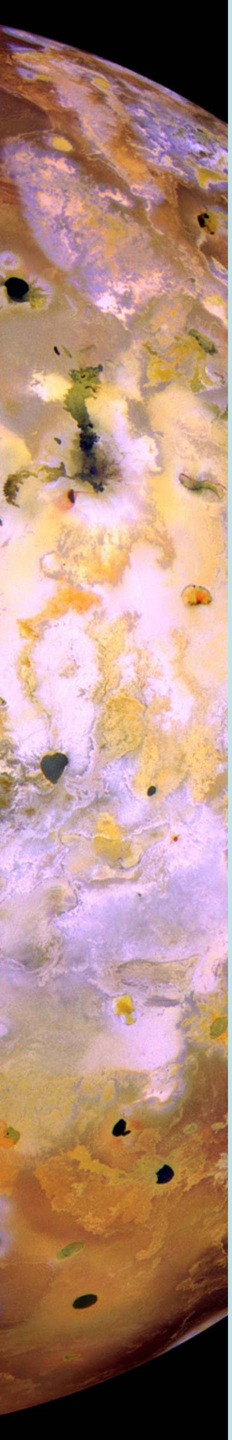
**partnered with APL**

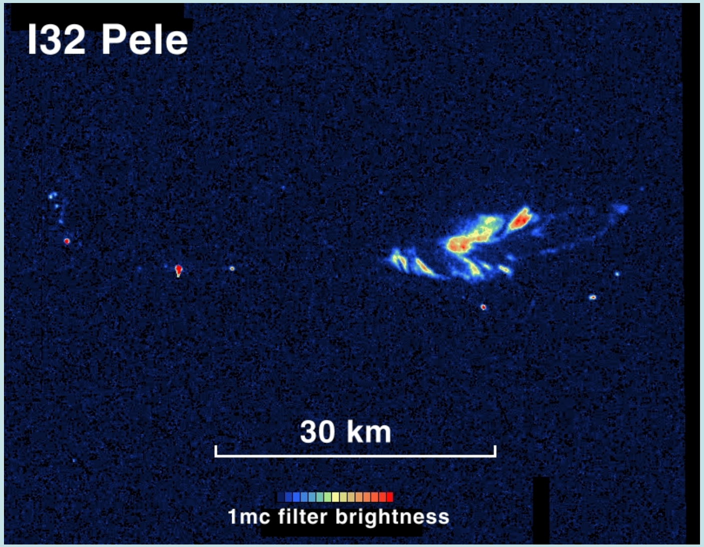
Lunar and Planetary Laboratory, University of Arizona
The Johns Hopkins University Applied Physics Laboratory
University of Bern
Swedish Institute of Space Physics
Jet Propulsion Laboratory
University of California at Los Angeles
German Aerospace Center



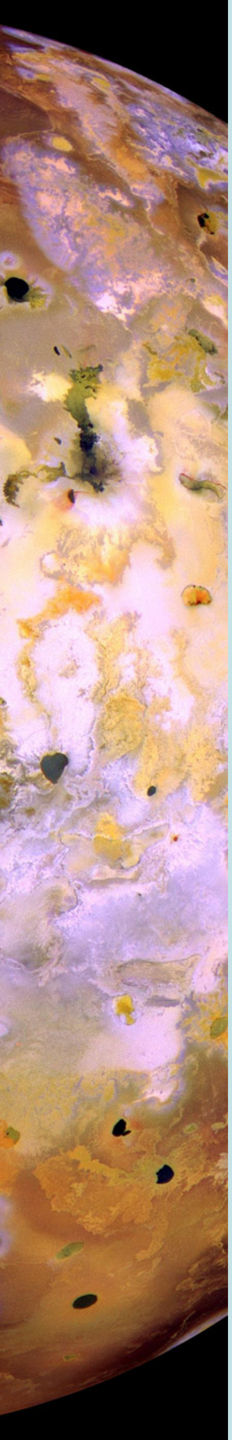
# *IVO* Science Objectives
## are to understand:

- **A1. Io’s active volcanism**
- **A2. Io’s interior structure and tidal heating**
- **B1. Io’s lithosphere and unique tectonics**
- **B2. Io’s volcanism-surface-atmosphere connections**
- **B3. Io’s mass loss and magnetospheric interactions**
  - ***What happens on Io doesn’t stay on Io***
- **B4. Limits to active volcanism on Europa**
- **C1. Jupiter system science**

These objectives are similar to those for the New Frontiers *Io Observer* concept.

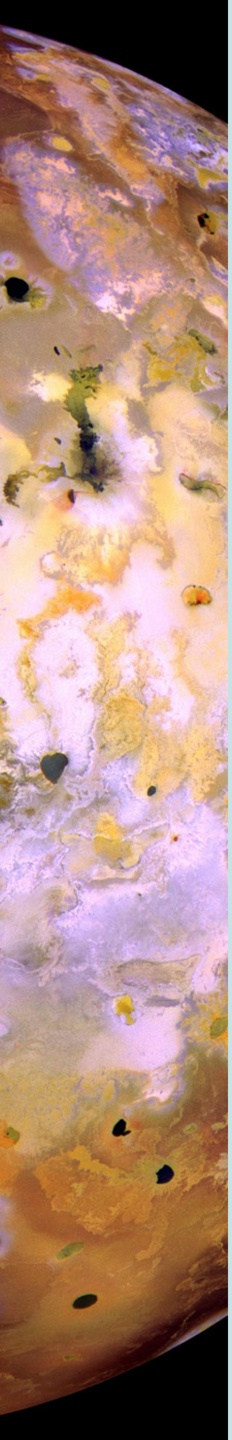



Lava glowing in the dark



# IVO has many measurement requirements, similar to *MESSENGER*

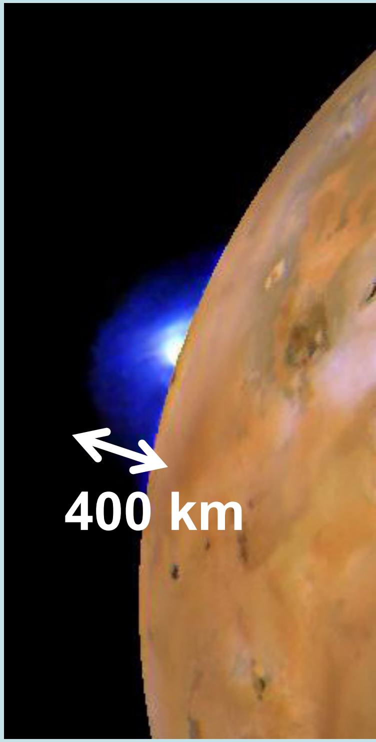
A1a. Document the variety and characteristics of volcanic landforms and vent structures.
A1b. Monitor active changes at Io's major volcanic centers.
A1c. Observe dynamic phenomena to measure velocities and effusion rates.
A1d. Document recent (~100 yr) volcanic history by mapping 150 K to ≥1000 K surfaces.
A1e. Measure the color temperature of erupting lavas.
A2a. Determine the melt fraction of the mantle from electromagnetic sounding.
A2b. Measure the thickness of Io’s lithosphere.
A2c. Measure or place new upper limits on Io’s internal magnetic field.
A2d. Map the global pattern of endogenic heat flow driven by tidal heating.
A2e. Determine whether regional topographic anomalies exist.
A2f. Measure tidal $k_2$ to constrain mantle rigidity
B1a. Image and map topography of representative landforms.
B1b. Search for structural changes since Voyager and Galileo imaging.
B2a. Measure neutral species in Io’s atmosphere and exosphere.
B2b. Observe $SO_2$, OI, and other emissions (in eclipse).
B2c. Map Christiansen Frequency (CF) to constrain $SiO_2$ of warm silicate lavas.
B2d. Map color variations.
B2e. Measure passive background temperatures to model diurnal T variations.
B3a. Measure neutral species in Io’s neutral clouds and plasma torus.
B3b. Monitor Na cloud and Io Plasma Torus.
B3c. Measure variability of plasma and magnetic signatures.
B4a. Search for plumes on Europa’s bright limb at high phase angles.
B4b. Monitor Europa’s surface color and albedo for changes over time.



# *IVO* Mission Overview

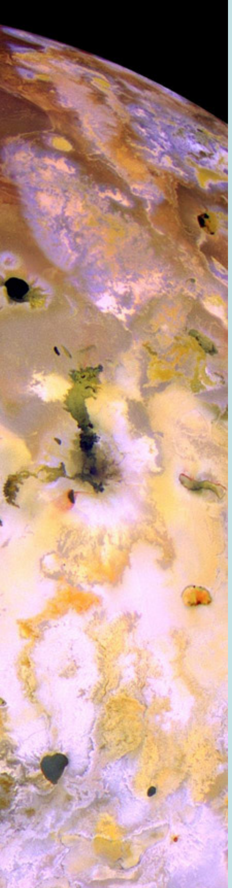
- Launch May/June, 2021
- ΔV-EGA (Earth gravity assist) trajectory, <5 years
- Asteroid flyby opportunities
- Jupiter orbit insertion (JOI) in February 2026 with 500 km Io encounter (I0)
- Capture into orbit inclined ~45° relative to Jupiter’s equator
- Eight additional Io encounters over 22 months
- Collect ≥20 Gb science data per encounter, ~100 times the Io data from the 8-year Galileo tour (~900 times total)
- Data playback near apoapsis
- Encounters last ~1 week, including global monitoring and four Io eclipses
- Distant monitoring of Io and Europa for activity throughout orbits
- Jupiter observations as permitted
- Extended mission options


Lava fountain on Etna



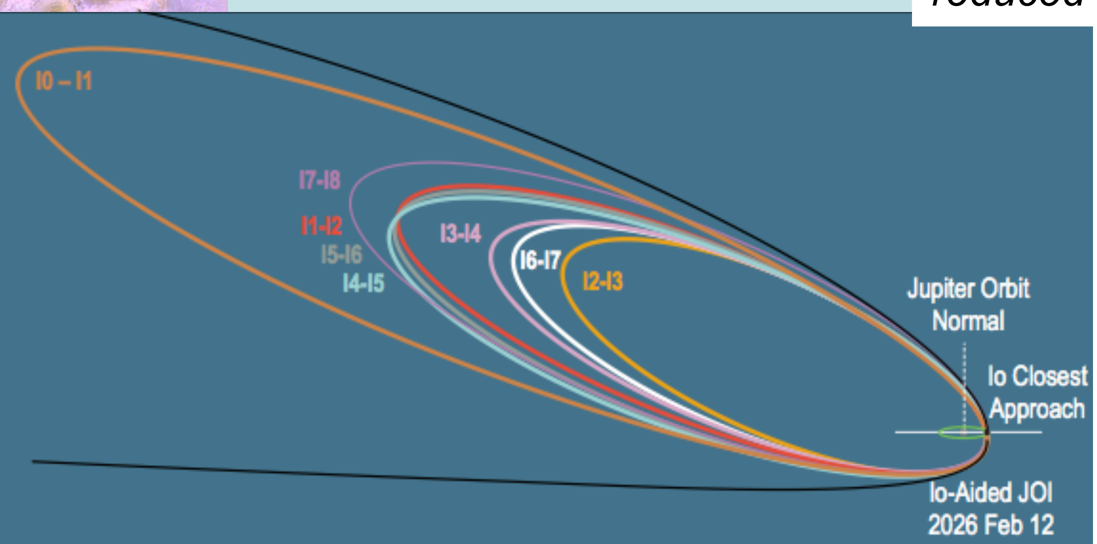

**Plume on Io**

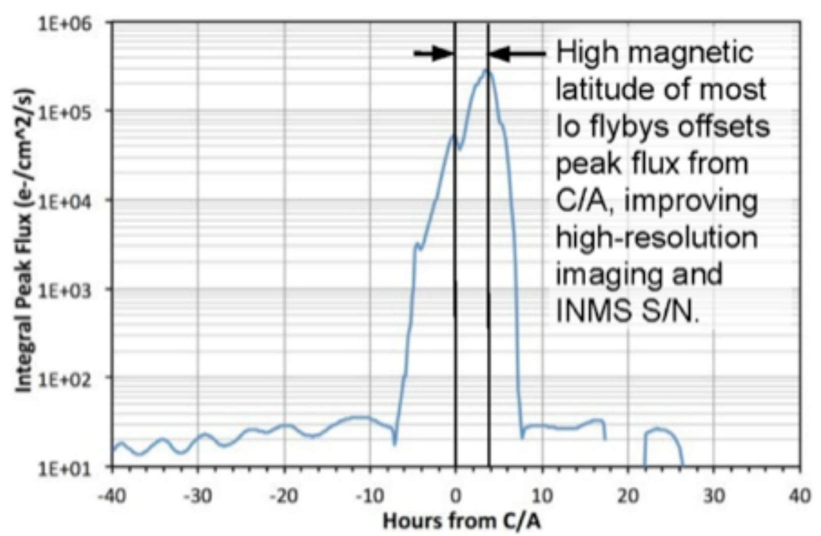
# *IVO* Orbit is optimized for Io science objectives *and* to minimize total dose

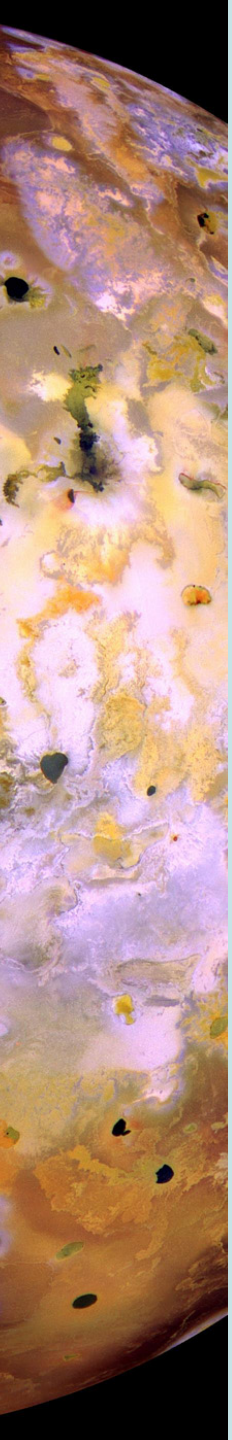


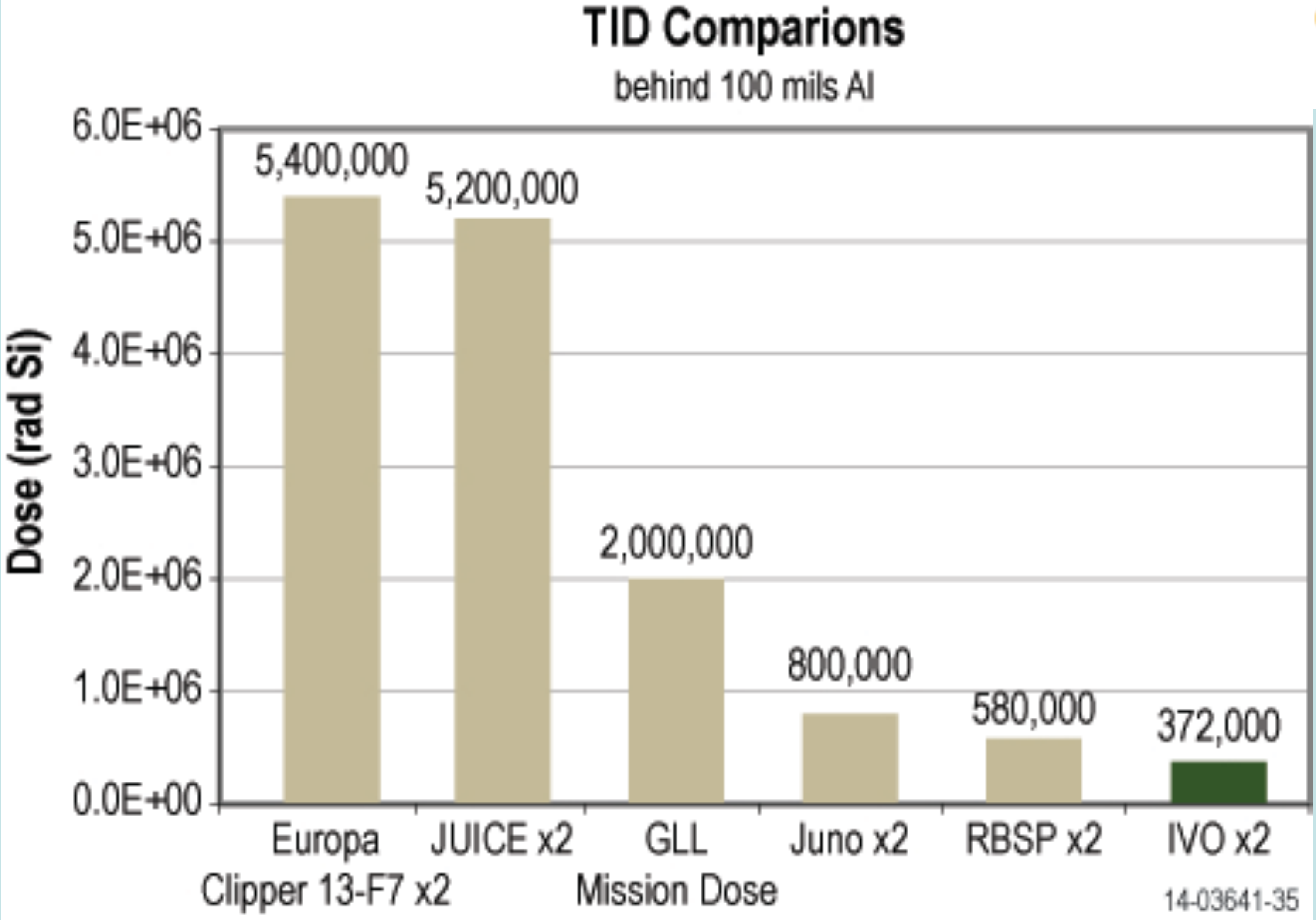
- Orbit inclined ~45º to Jupiter's orbital plane
- Nearly north-south flybys of Io has significant advantages
  - Minimizes total dose per flyby
    - ~20 krad per flyby (v. ~80 for Galileo)
    - S/C only spends ~15 hrs/flyby in the intense radiation
  - Can get closer to Io with low radiation noise for imaging faint emissions
  - Pole-to-pole flybys are best for magnetic probing of Io's interior
  - Good polar observations to distinguish between tidal heating mechanisms
  - Slowly changing subsolar longitudes on Io are best for change detection
    - ~1-2 month orbital period

*Below right:*
*Integral peak flux (1-cm Ta equivalent shielding) is reduced by 4 orders of magnitude <10 h from C/A.*



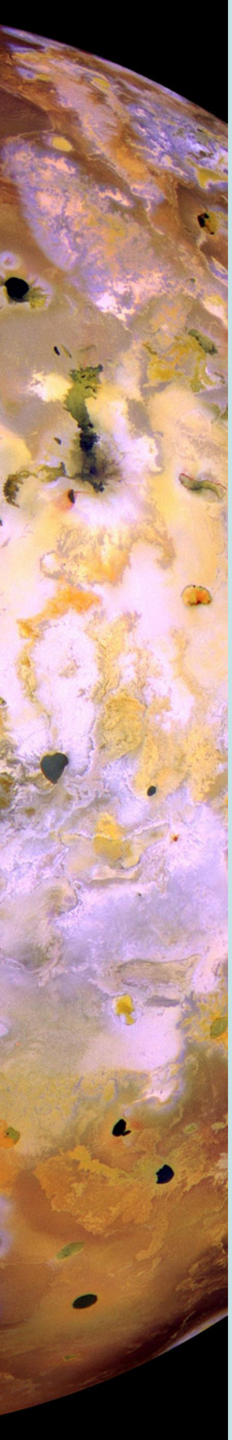


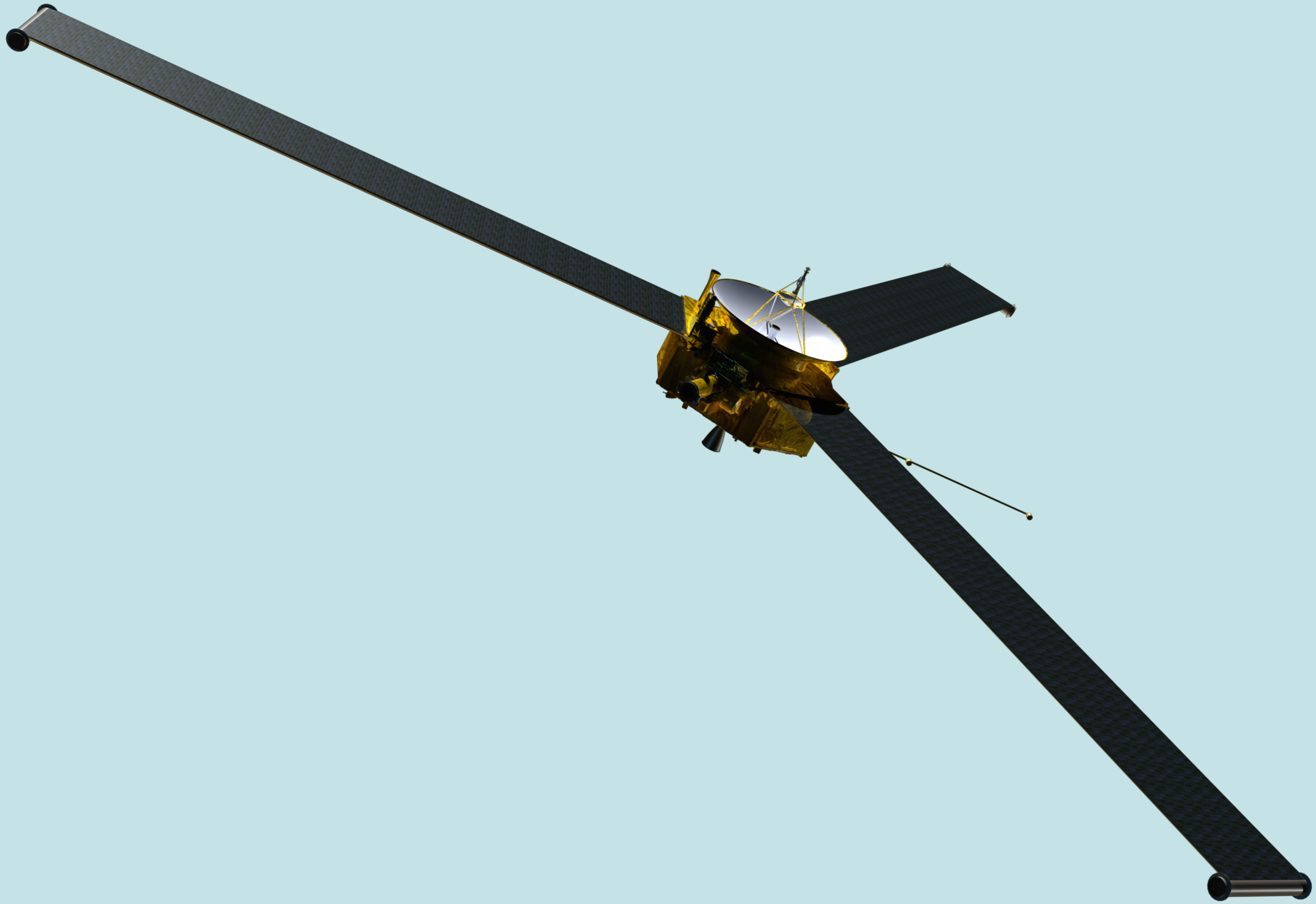



A comparison of dose-depth estimates for missions at 100 mils Al demonstrates the TID estimate for *IVO* is well below that of other Jupiter orbiter missions.

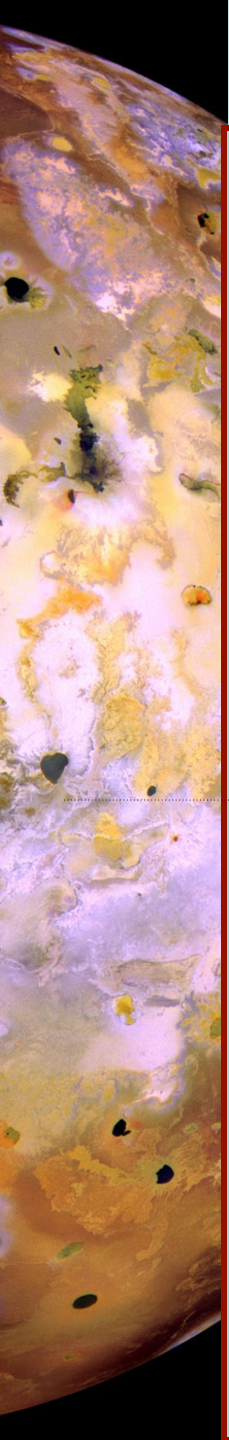
# *IVO* will advance NASA Technologies

1. Lightweight Roll Out Solar Arrays (ROSA)
2. Deep Space Optical Communications (DSOC)

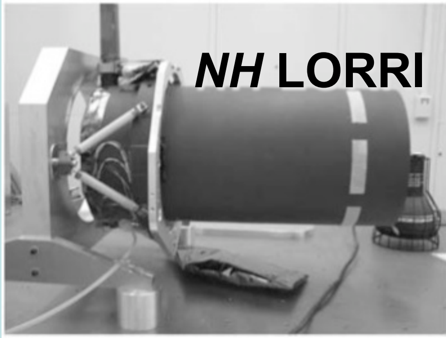


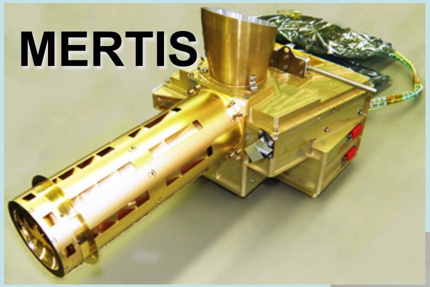


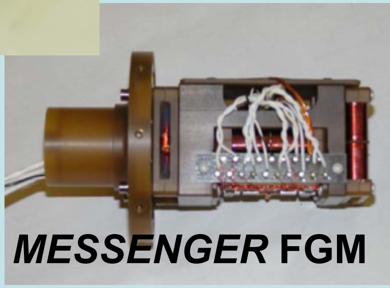
# Science Payload



- **Narrow- and Wide-Angle Cameras (NAC/WAC)**
  - NAC (5 μrad/pixel) and WAC (218 μrad/pixel) for stereo; 11 color bandpasses
- **Thermal Mapper (TMAP)**
  - 125 μrad/pixel, 7 bandpasses from 5-14 microns plus radiometer (7-40 microns)
  - DLR, MERTIS heritage
- **Dual fluxgate magnetometers (DMAG)**
  - UCLA, multi-mission heritage
- **Particle Environment Package for Io (PEPI)**
  - Ion and Neutral Mass Spectrometer (INMS), Plasma Ion Analyzer (PIA), Integrated electronics
  - JUICE/PEP designs
- **Student-collaboration Hotspot Mapper (HOTMAP)**
  - Wide-angle camera 1.5-2.5 micron bandpass

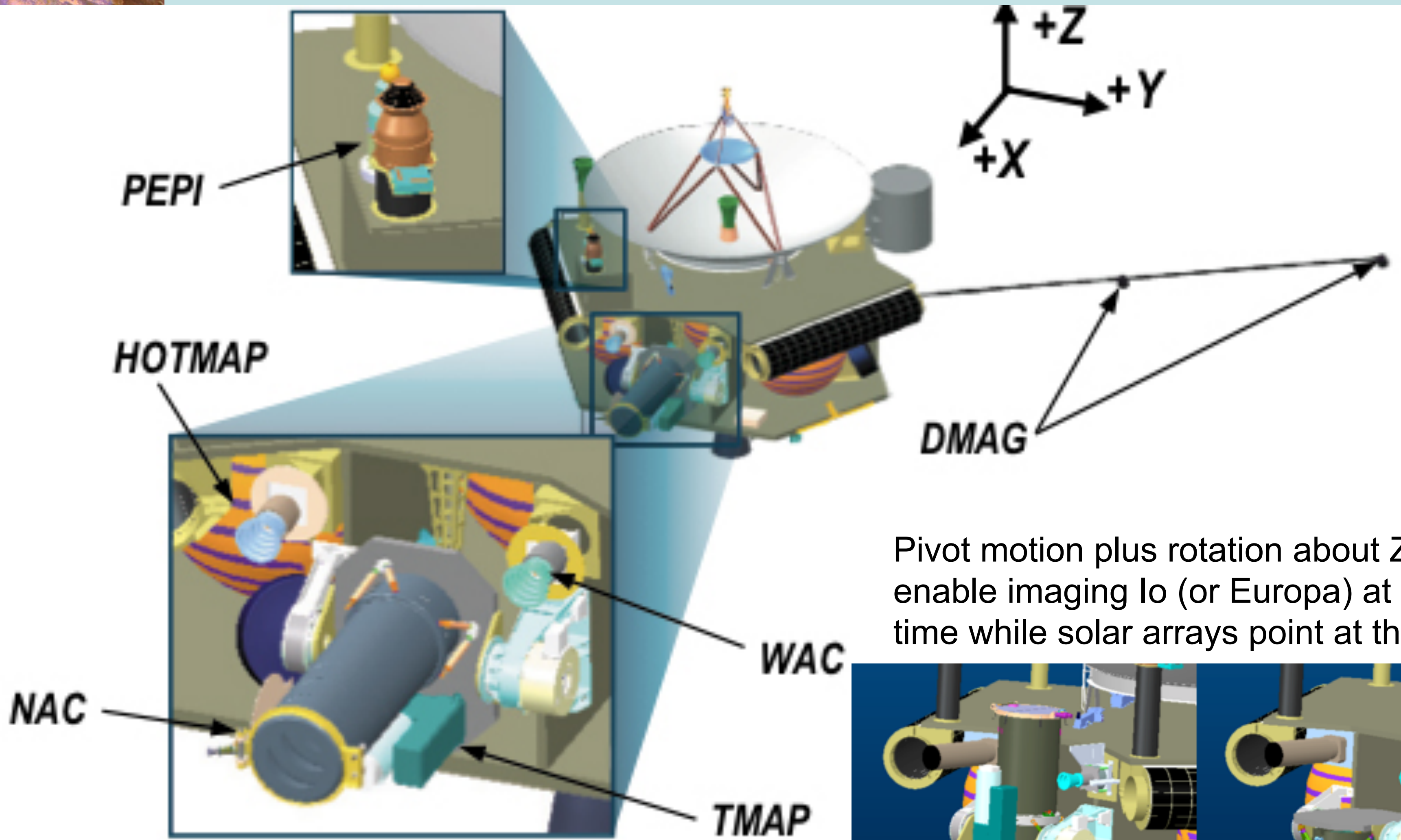


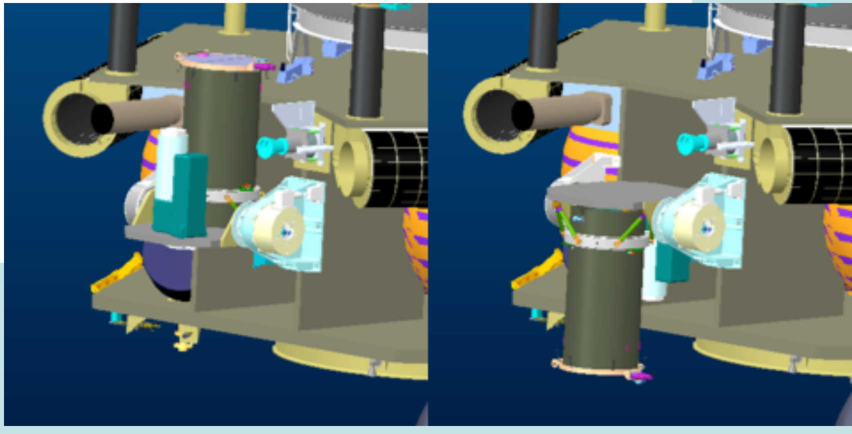





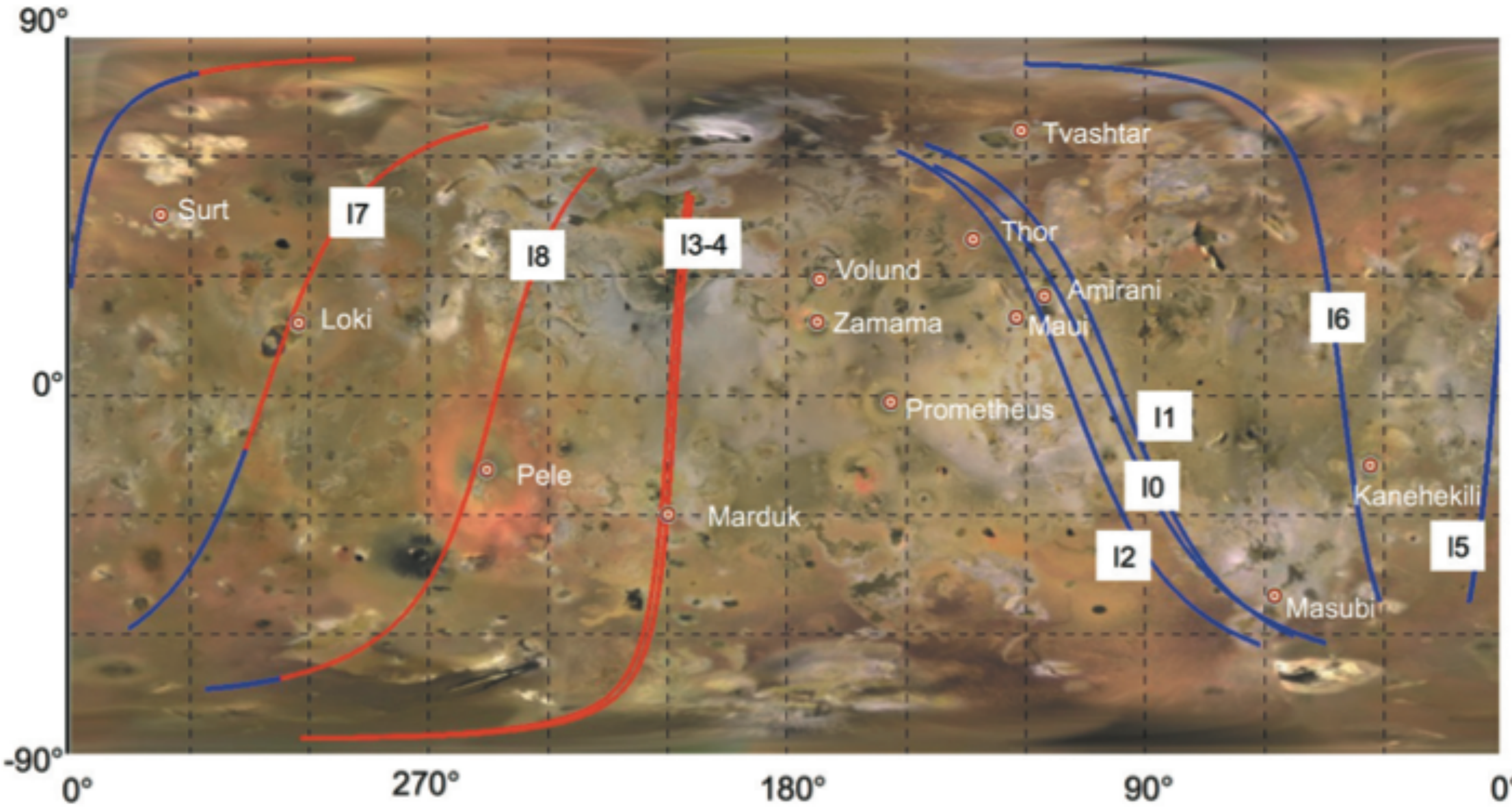
# Science Instruments on S/C




Pivot motion plus rotation about Z axis enable imaging Io (or Europa) at any time while solar arrays point at the sun.

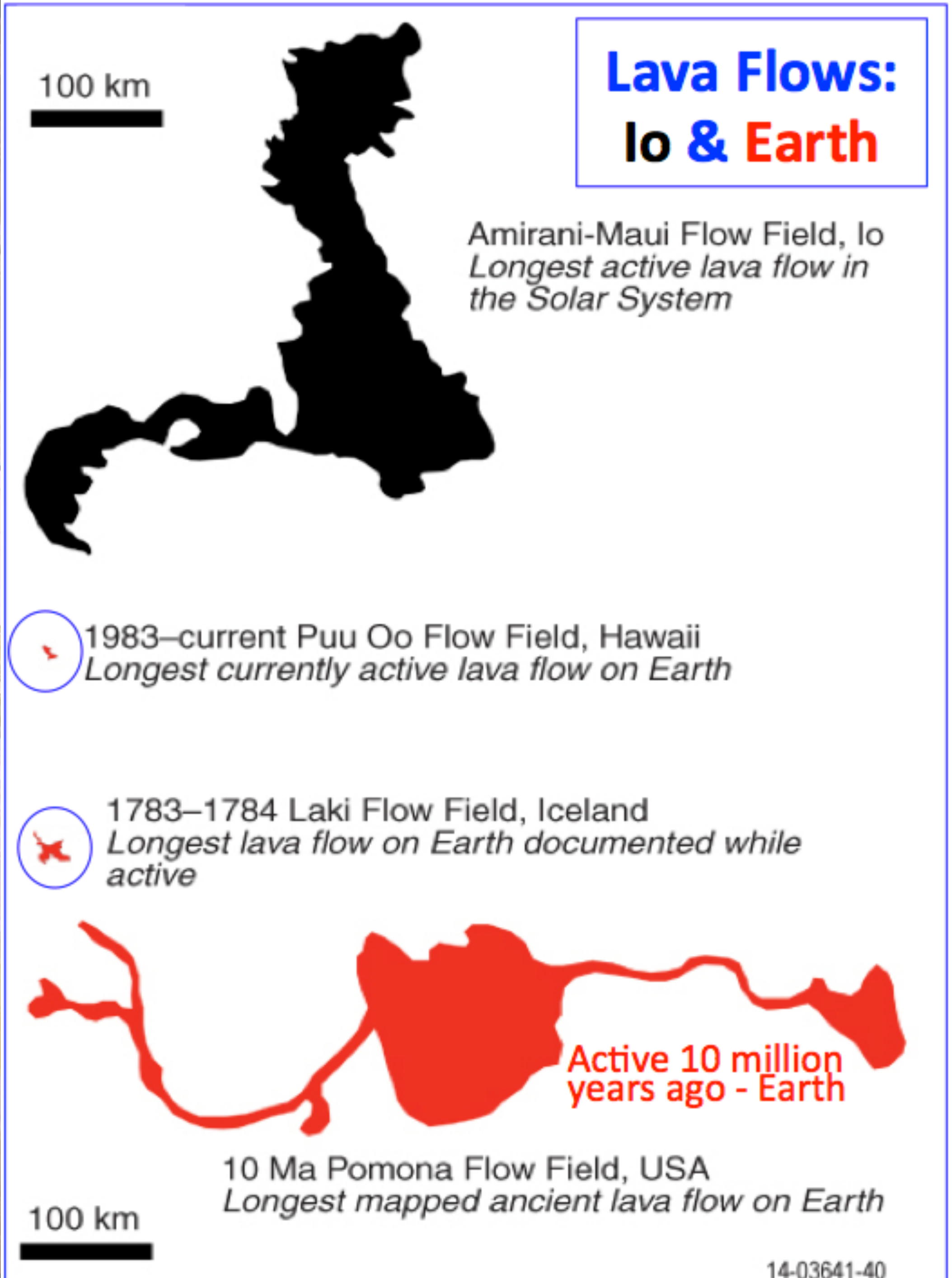


# Jupiter Tour and Io Groundtracks



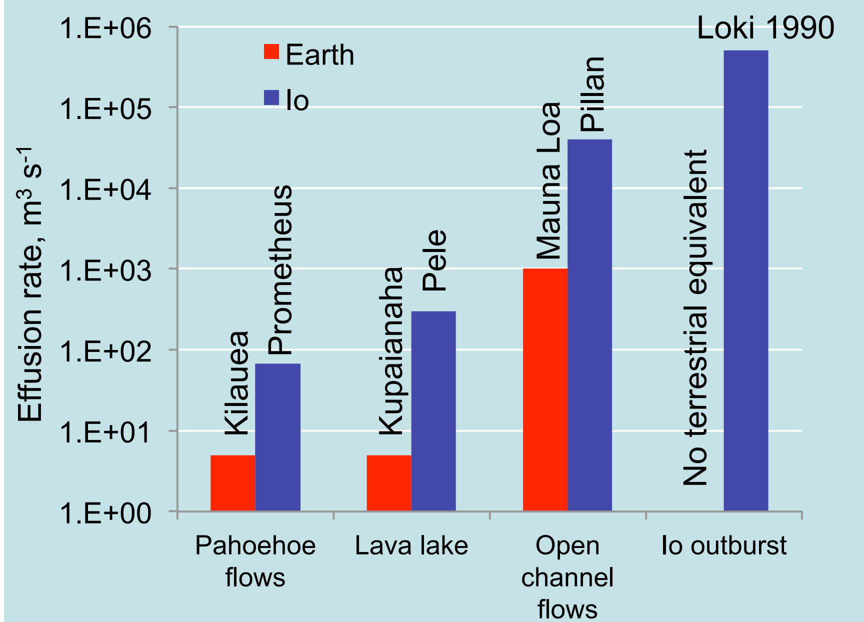

Pele plume flythough New Years Eve 2028!

# Lava Flows: Io & Earth



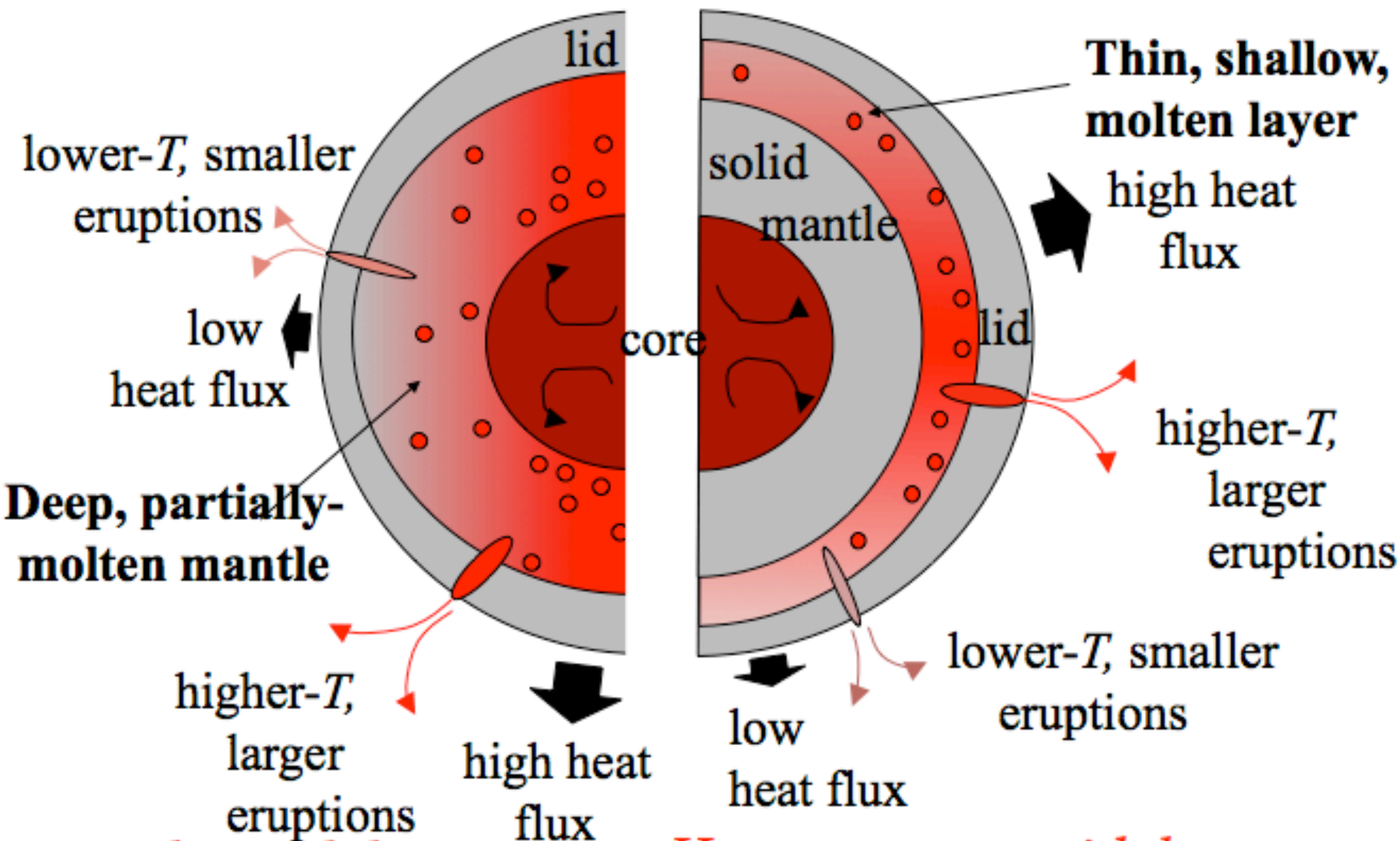

- Effusion rates 10-100x greater on Io than on Earth (today) for comparable eruption styles.
- Io allows us to directly observe the formation of giant lava flows and ash deposits as have occurred on the Earth, Moon, Mars, Venus, Mercury.
- Many questions about lava emplacement processes and the effects thereof can be answered by repeated imaging.

Effusion rate comparisons – contemporary eruptions



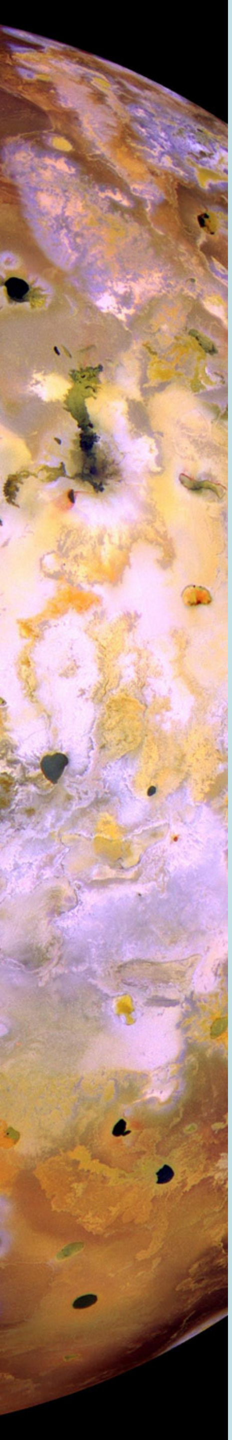
## DISTRIBUTED HEATING "deep mantle"

## SHALLOW HEATING "asthenosphere"



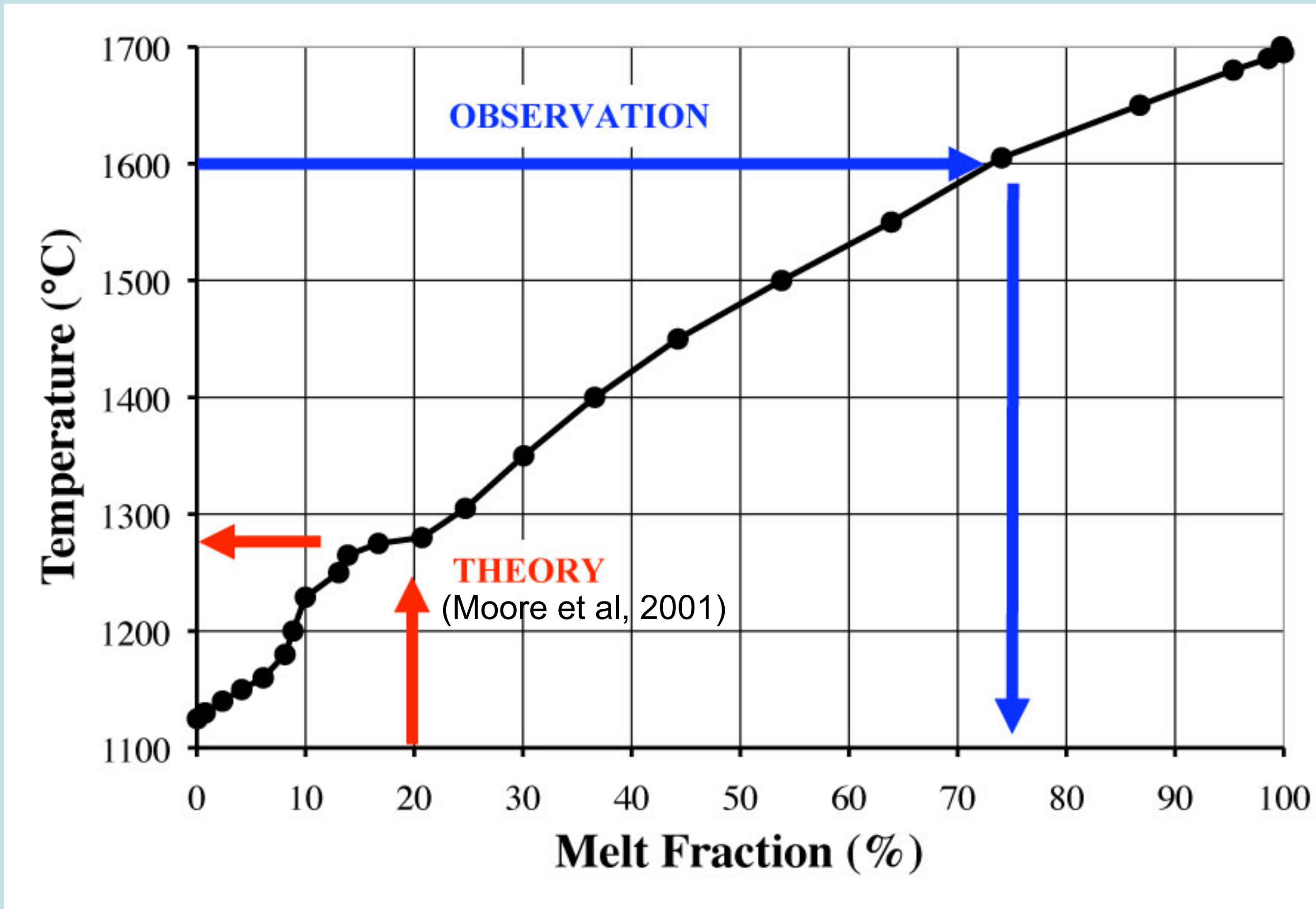

*Hotter poles with larger eruptions, thicker crust*

*Hotter equator with larger eruptions, thicker crust*



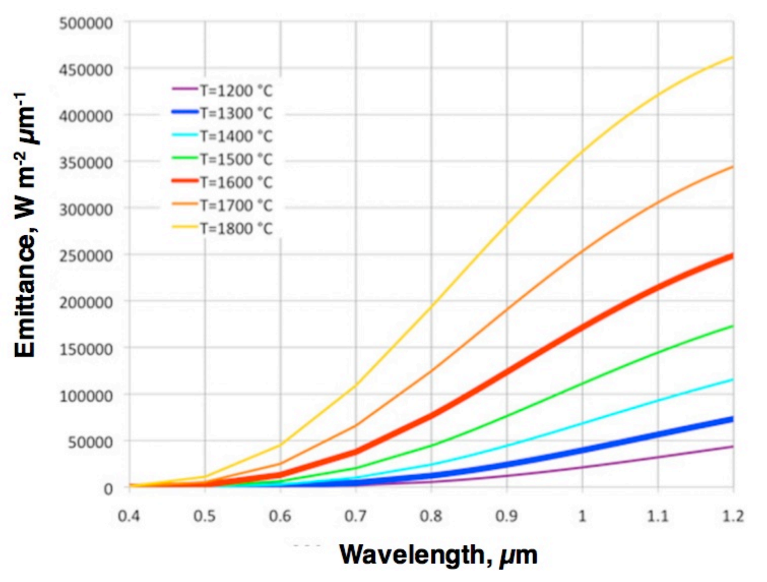
# Are there really lavas >1400°C (>1673 K)?

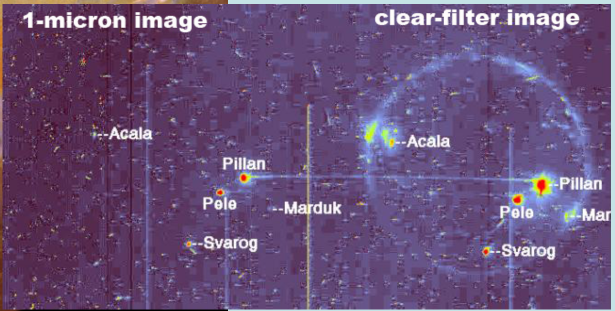
- Peak temperature reports (up to 1600º C) suggest Io’s mantle has a high degree of melt [Keszthelyi et al. 2007], but that could lead to insufficient tidal heating.
- High temperatures suggest ultramafic eruptions, like those on early Earth, Moon, Mercury, and Mars



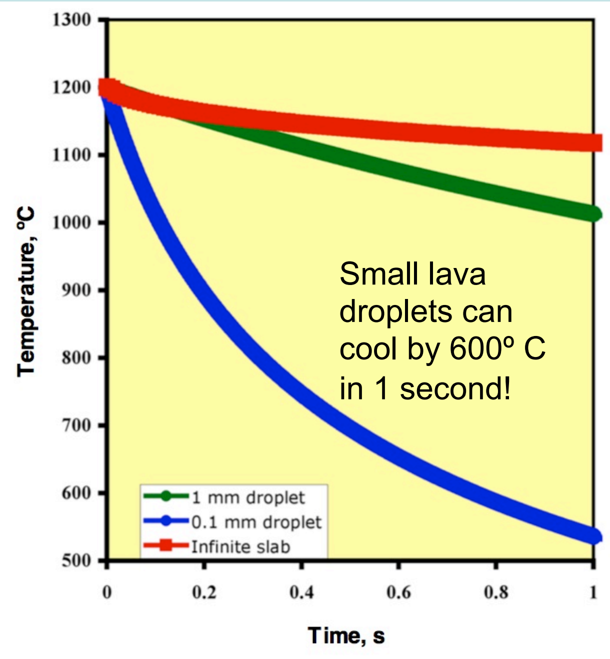
# *IVO* Cameras designed to measure liquid lava temperatures

- Liquid lava glows at visible to near-IR wavelengths
- *Galileo* SSI detected hot lavas and we did our best to measure temperatures, but there were many limitations
  - Saturated data, poor SNR, limited coverage
  - Data in different color bandpasses were separated in time by many seconds or minutes, so ratios could give erroneous Ts
- Requirements for *IVO* camera design
  - Measure temporal variability (up to 60 Hz) and acquire pairs of colors near-simultaneously (<0.1 s)
  - Unsaturated data, high dynamic range
  - Shielding and fast readout to limit radiation noise



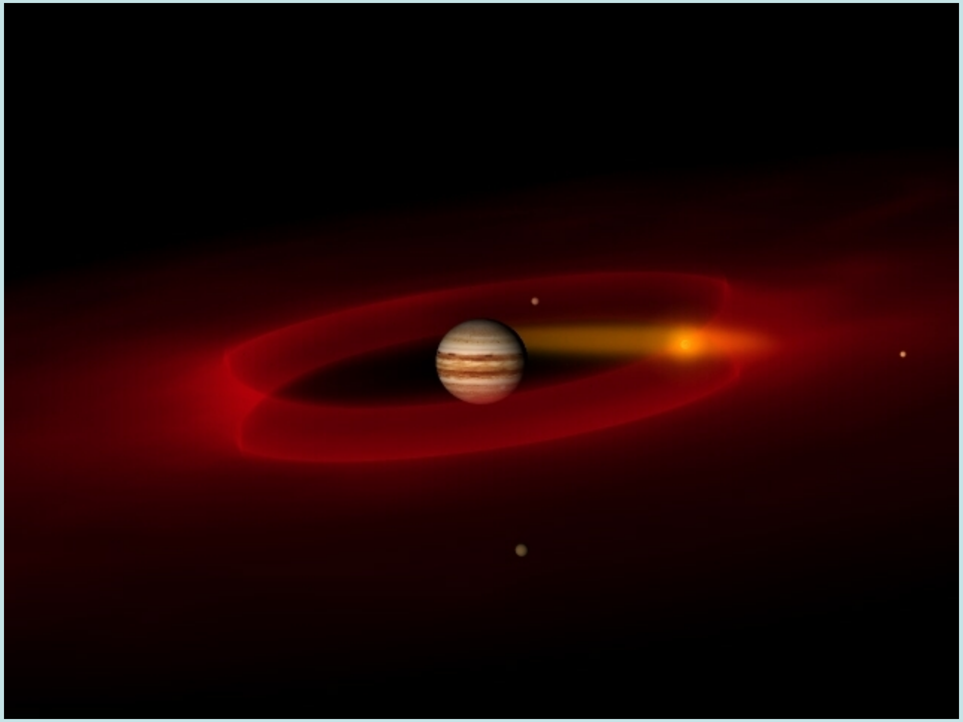

*Galileo* eclipse images (on-chip mosaic of images acquired minutes apart) during the initial outburst (lava fountaining) from Pillan Patera, used to estimate lava temperatures (McEwen et al., 1998)



# Jovian Magnetic Field at Io

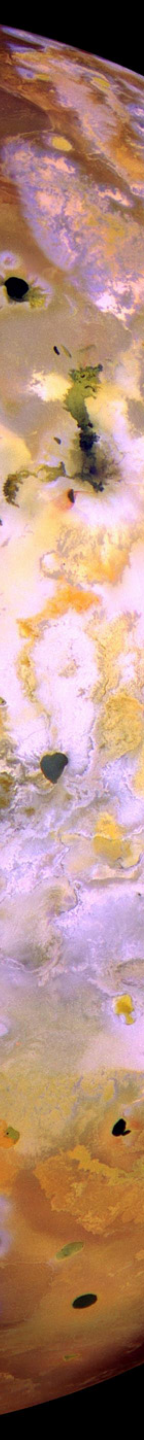
The ~10° tilt of the Jovian dipole moment relative to planetary rotation axis yields a variable field at Io.

Over one Jovian rotation (13 hours in Io frame), the radial component of the field (By) at Io varies by ~1500 nT.



This imposed variable field will cause an induction response in Io’s conducting mantle.

The amplitude of the induction response and its phase relative to the imposed variable Jovian field are indicators of the depth of the outermost conducting layer and of its conductivity.



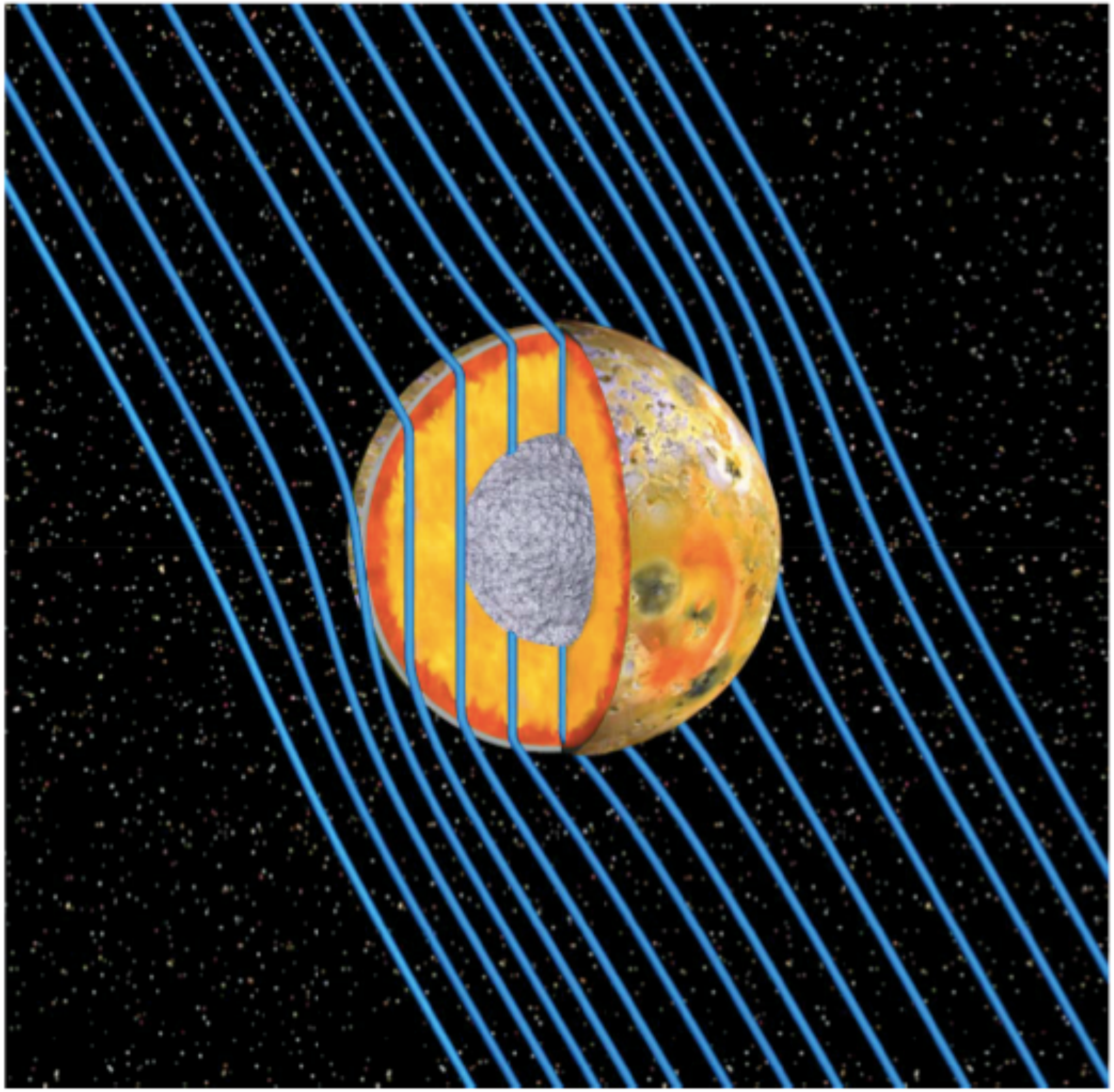
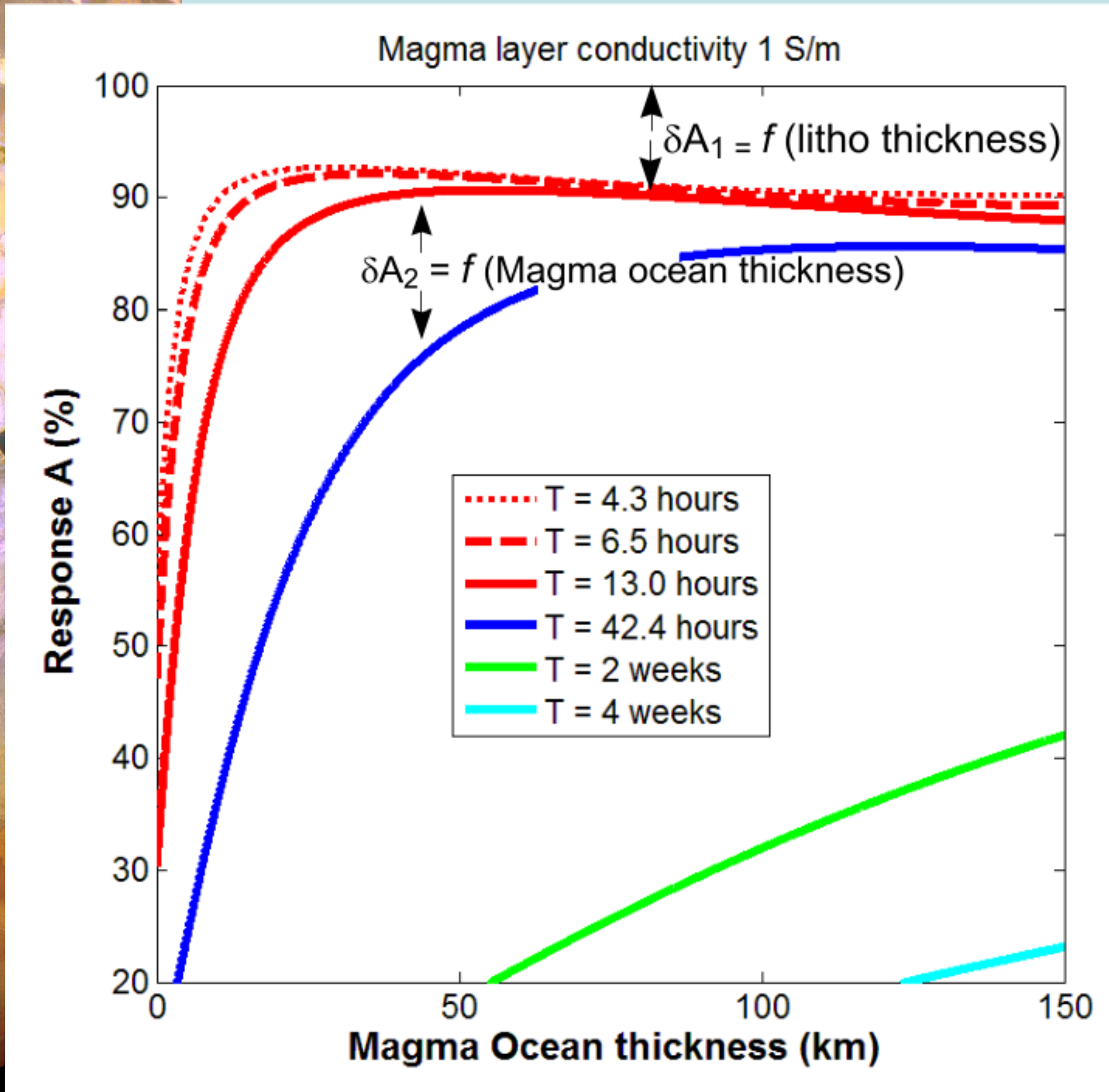


**Fig. 4.** The internal structure of Io as revealed by the present study. Underneath a low-density crust 30 to 50 km thick (gray outline in the cross section) exists a global magma layer (asthenosphere) with a thickness exceeding 50 km and a rock melt fraction of a few tens of percent (red-brown outline). The high electrical conductivity of the asthenosphere prevents the time-varying horizontal component of the jovian field from significantly penetrating into the mantle. The almost constant vertical magnetic field pervades the ultramafic mantle (golden hues in cross section), which must have a temperature exceeding 1200°C to support rock melts in the asthenosphere. The 600- to 900-km-radius core composed of Fe-FeS is rendered in a metallic silver hue.

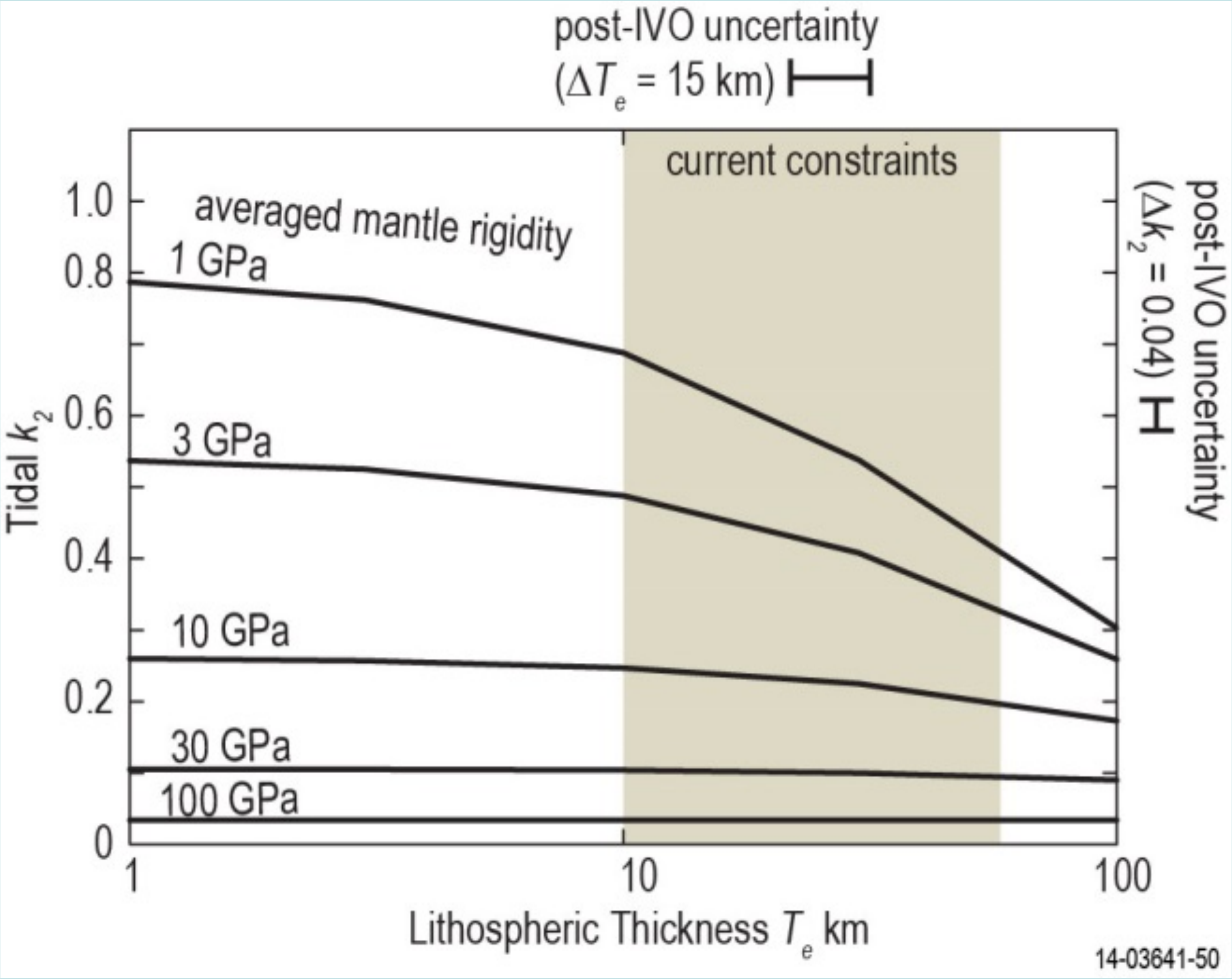
Khurana et al., 2011, Evidence of a Global "Magma Ocean" (or >20% interconnected melt) in Io's Interior (Science 332, 1186).

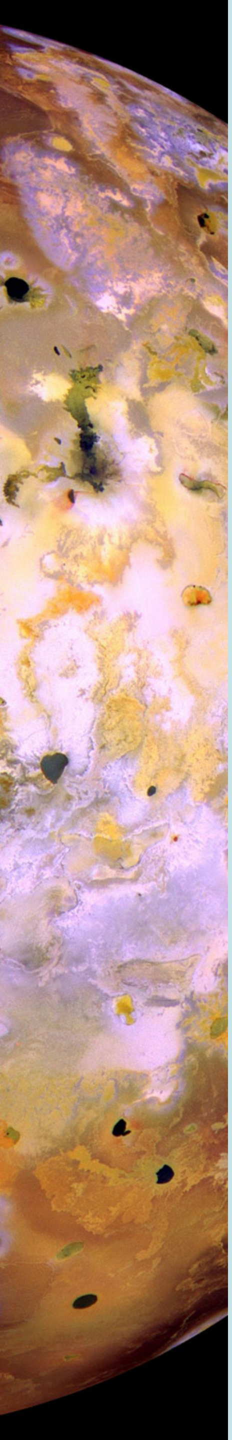
# *IVO* will go well beyond *Galileo* magnetic induction results




- 4 orbits optimized to minimize plasma effects (high-low magnetic latitude pairs over trailing hemisphere)
- PIA measurements used as a constraint on MHD models of plasma interactions
  - All 9 orbits useful
- Multi-frequency induction (42.4-h orbital period, 13-h synodic period and 2x and 3x harmonics) enables penetration to varying depths
  - Can measure global average lithospheric thickness
  - Constraint on thickness and conductivity of partially molten layer

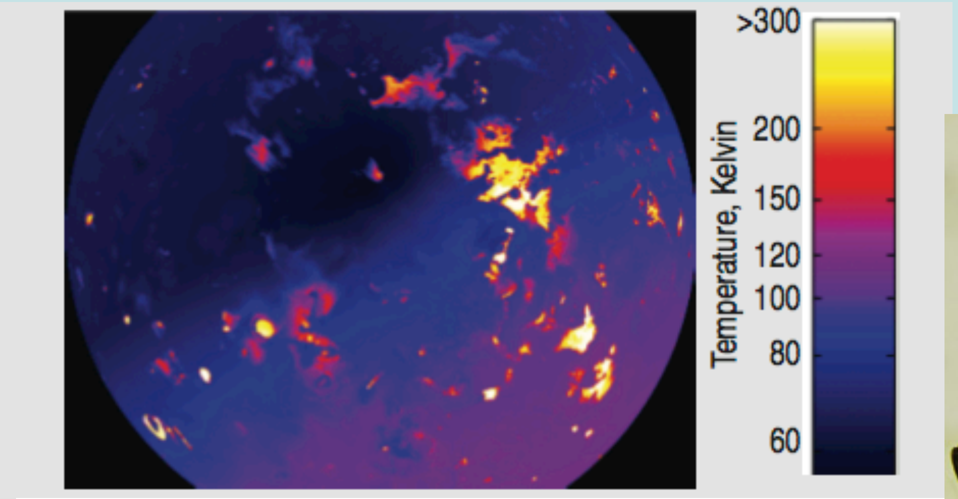
# Gravity and magnetic data combine to measure mantle rigidity



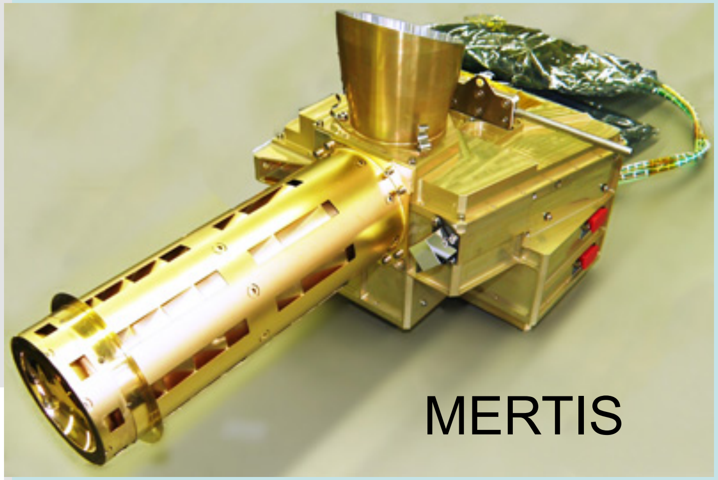


# Thermal Mapper (TMAP)

- **5-40 microns to monitor volcanism and measure heat flow**
  - Io surface Ts range from 80 to maybe 1900 K!
    - (Mercury T range is ~90 to 700 K)
- **Thermal emission compositional studies of silicate mineralogy**
  - Lava expected to be glassy--problem for NIR but not thermal IR
- **Instrument**
  - 4.6 deg FOV, 250 urad/pixel, 1 km/pixel from 4,000 km, 8 bandpasses
  - 640 x 480 pixel detector
  - Microbolometers and radiometers are not sensitive to radiation-induced noise

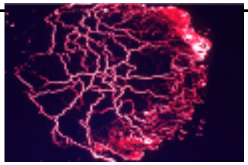



TMAP will provide global temperature (and derived heat flow) maps of Io at >10x improved resolution over *Galileo* PPR

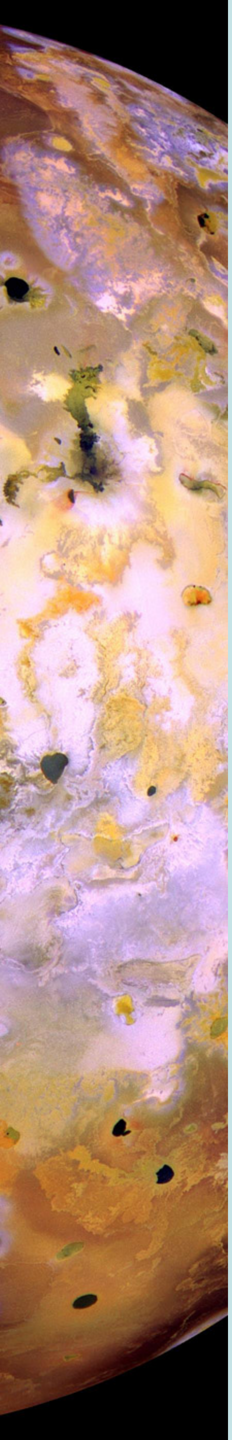


MERTIS

## Thermal Signature and Evolution of Different Eruption Modes

| | Eruption type | Location | Thermal characteristics | Short-timeframe change | Long-timeframe change |
|---|---|---|---|---|---|
|  | Lava fountains | Fixed | Intense short wavelength thermal emission. Very high flux densities. Highest colour temperature. | Very short duration (~hours?). | Not seen unless event repeats: emission rapidly decays with time. |
|  | Lava lake | Fixed | Variable flux density. Variable colour temperature. | Brief periods of overturning and enhanced thermal activity. | Persistent hot spot, part of cycle of activity. |
|  | Ponded flow (stagnant flow) | Fixed | High to low flux density. High to low colour temperature. | Fixed location, cooling with time like a lava flow. | Thermal emission follows predictable cooling curve to extinction or renewal. |
|  | Channalized flows, sheet flows | Wandering | Higher flux density than insulated flows. Initial high colour temperature. | Thermal source increases in size. | Flows eventually stop and cool. |
|  | Insulated and tube fed flows (pahoehoe flows) | Wandering, persistent thermal source. | Low flux density. Low colour temperature. | Source increases in area in downslope direction. | Source migrates and increases in size with time. Lava tubes form. |
|  | Lava domes | Fixed. Gradual increase in size. | Low flux densities. Very low colour temperature. | Small incandescent areas: occasional explosive activity. | Weeks-months. Not identified on Io. |

Davies, Keszthelyi and Harris, 2009



# Mapping CF demonstrated by *LRO* Diviner and also with field spectrometers on cooling lavas in Hawai'i

Best remote-sensing method to determine composition of fresh glassy lavas (glass reduces NIR absorptions)

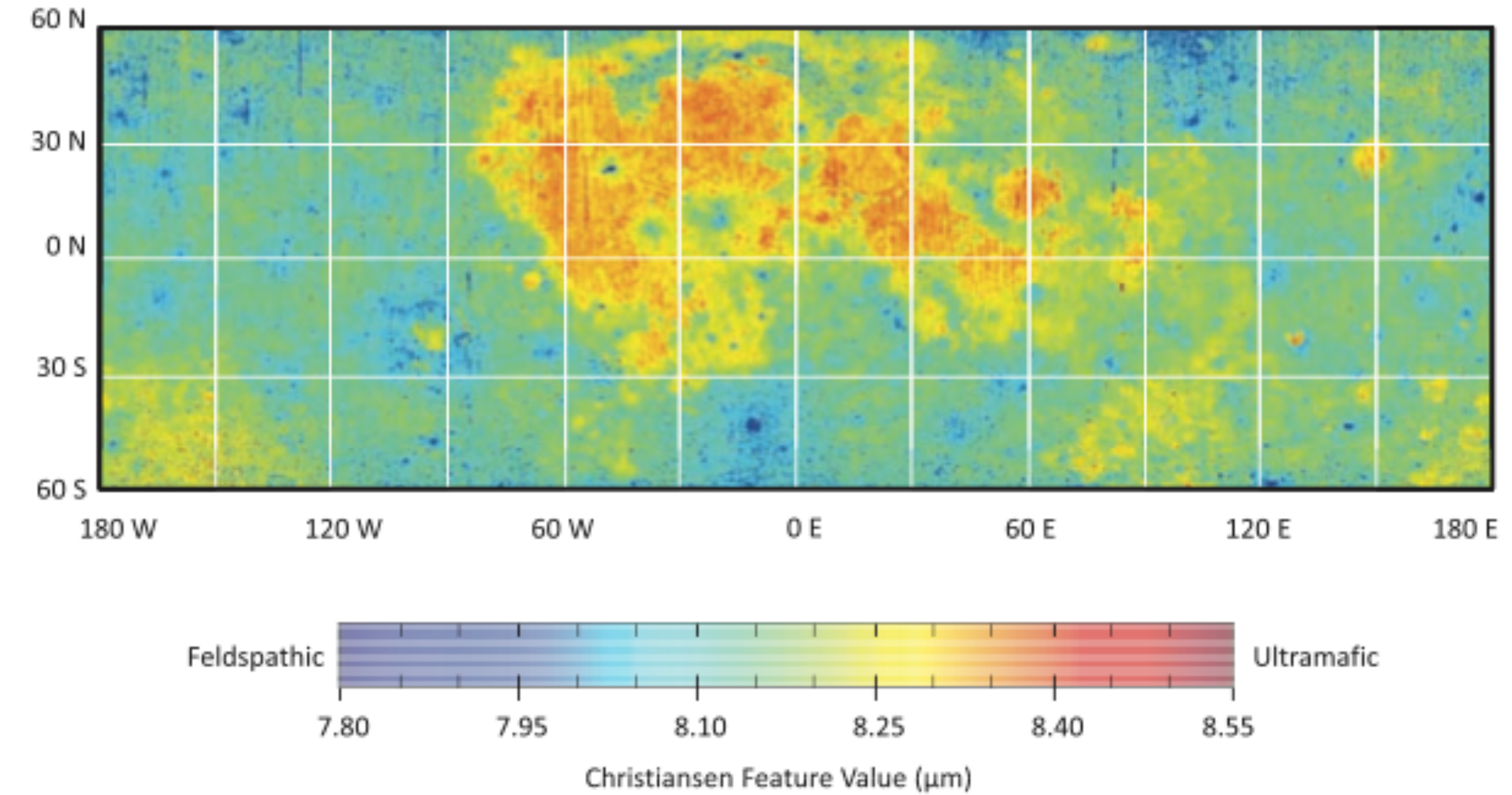
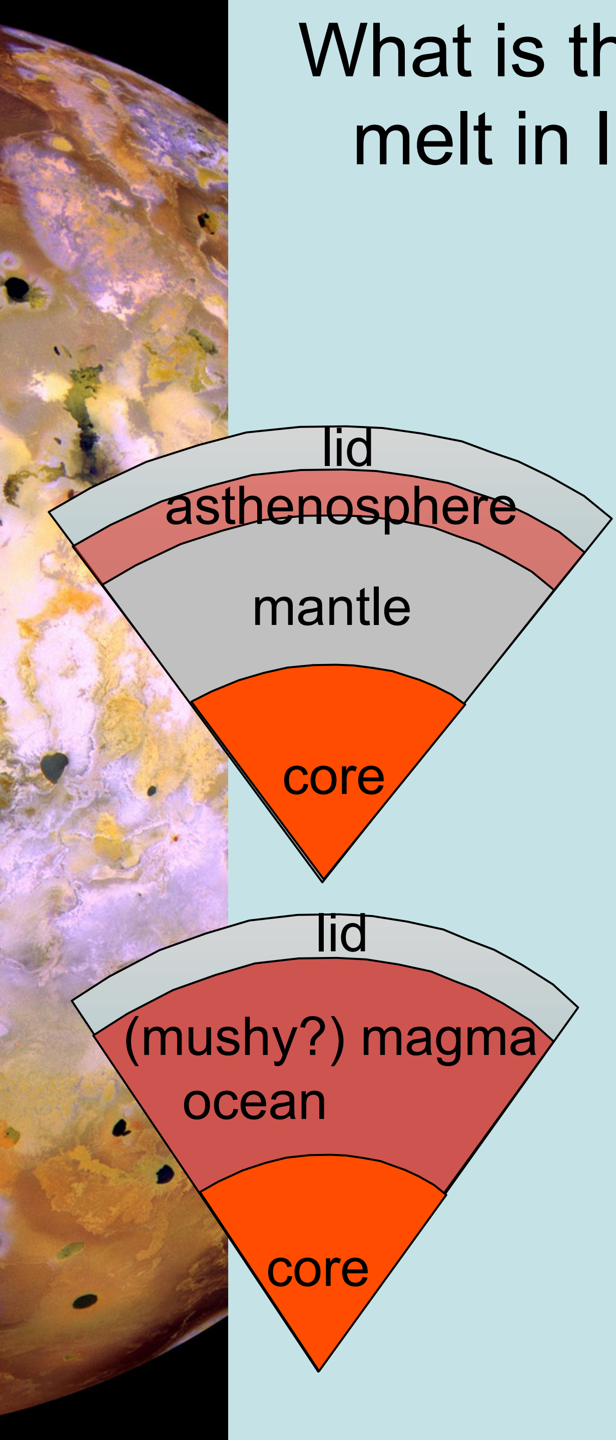



**Fig. 2.** CF value map of silicate mineralogy. The color map was chosen to highlight compositional variability of common lunar terrains and saturate blue or red for unusual compositions (Fig. 3). This map uses a pyramidal spatial resolution structure between 8 and 0.5 pixels per degree.

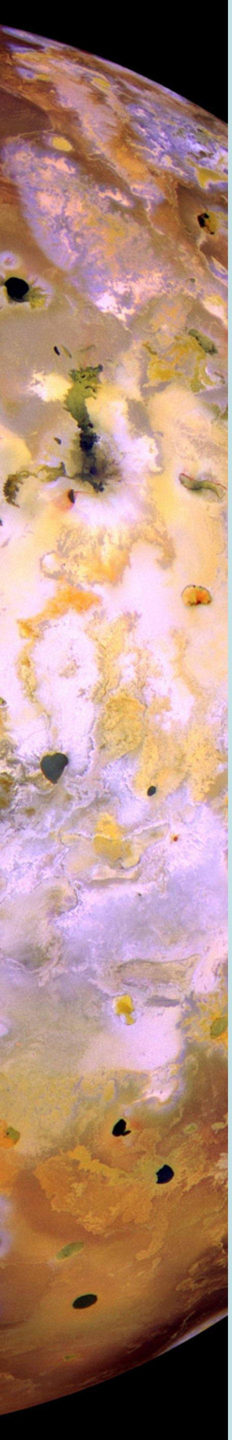
Global Silicate Mineralogy of the Moon from the Diviner Lunar Radiometer, Greenhagen et al., Science 329, 2010

# What is the distribution and abundance of melt in Io's interior, key to testing tidal heating models?



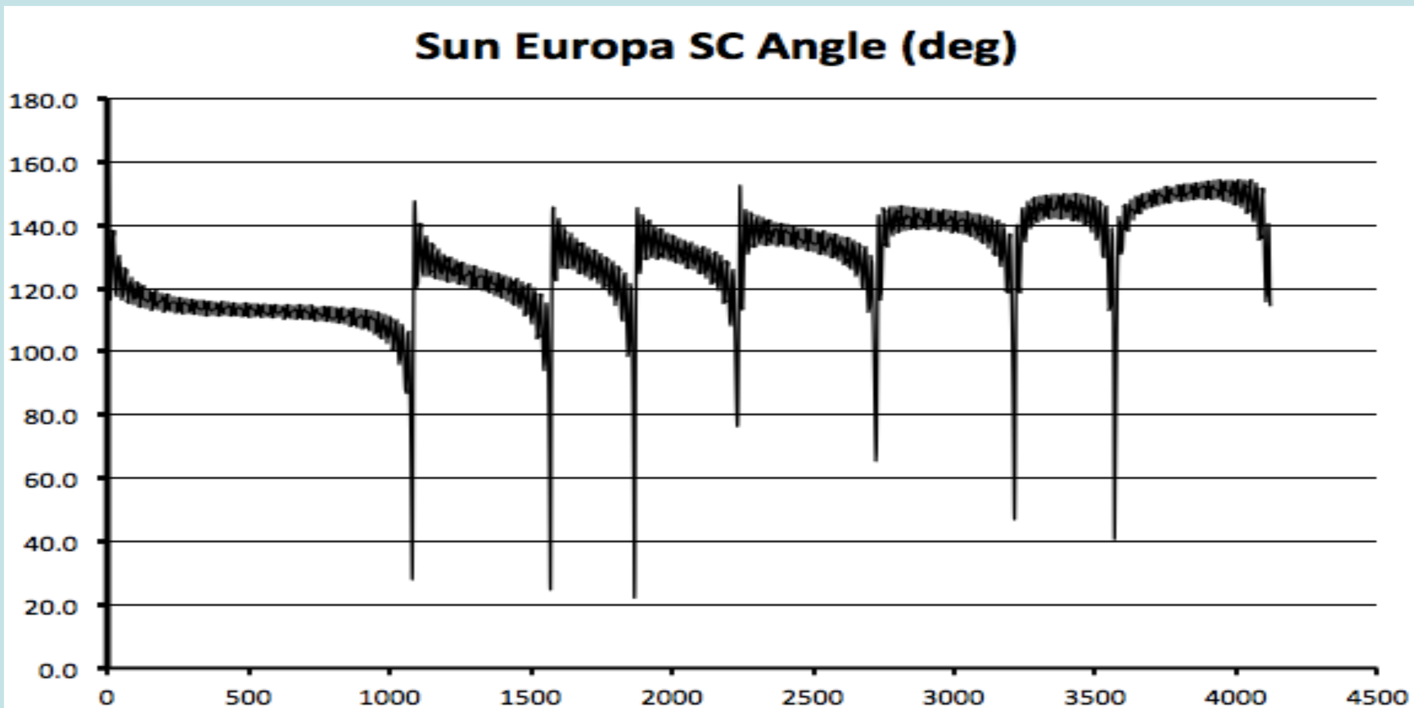

***IVO* can address this question in multiple ways:**

- Determine peak lava temperatures and pattern with latitude (NAC/WAC)
- Measure induced magnetic response (DMAG)
- Gravity science Re($k_2$) and mantle rigidity
- Large-scale topography (NAC/WAC)
- Heat flow mapping (TMAP) provides a test of tidal heating models if a pattern with latitude is clear.
- Determine silica content of lavas (TMAP), related to degree of mantle melt.

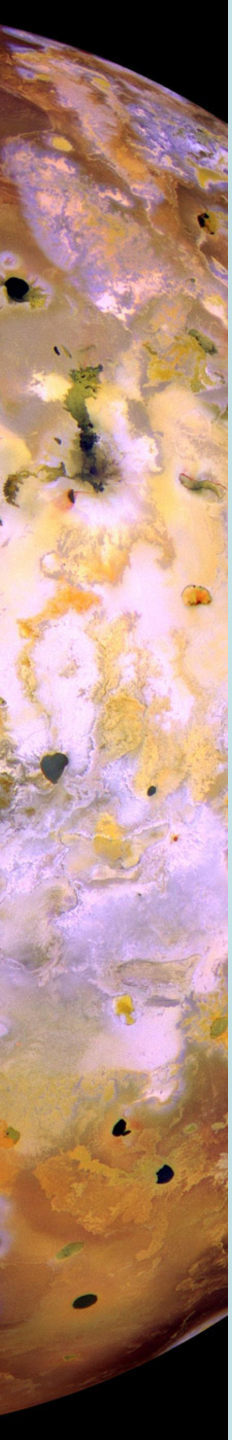


# *IVO* Provides Excellent Search/ Monitoring of Europa plumes!

- Past optical searches are *very poor!*
- *IVO* can improve on this by several orders of magnitude—extended time at high phase angles and 2-20 km/pixel; near-UV and clear bandpasses
  - Cover all limb longitudes and true anomalies
- Plumes on Europa much more likely <40 km high (Quick et al. 2013), than ~200 km of HST UV emissions

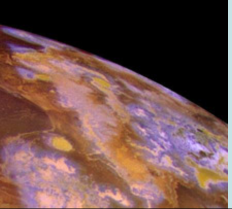



3-hr time steps past JOI



# Science Enhancement Options

- **Mainbelt Asteroid flyby**
  - Io dress rehearsal as well as asteroid science
- **Add ~20 Participating Scientists**
- **Earth-based observing campaign**
  - Support for travel and data analysis
- **Extended Mission**
  - Radiation design and other margins should permit 9 additional Io encounters
  - Option 1: pump orbit out for 6-year extension
    - ½ Ionian year so opposite sides in day/night at closest approach
    - Possible encounter with outer irregular moon (captured KBO?)
    - *IVO* could observe jointly with *JUICE* and *Europa Clipper* (TBD arrival) for Jupiter system science



# IVO Fact Sheet

Ask me for a copy

IO VOLCANO OBSERVER

*Investigating the Solar System's most volcanically active world*

*Io, the innermost of four large Galilean moons of Jupiter, is the most tidally heated and volcanically active world in the Solar System. The enormous volcanic eruptions, active tectonics, and high heat flow are like those of ancient terrestrial planets and present-day extrasolar planets. Powered by advanced solar array technology, IVO's dedicated mission design and optimized payload of remote sensing and particle and fields measurements will transform our understanding of this unique world.*

Tupan Patera (from Galileo)

**PI: Alfred McEwen, University of Arizona**

**Mission Implementation: JHU/APL**

### Impact and Relevance:

*IVO addresses major themes identified in the 2011 Decadal Survey for Planetary Science:*

- **Workings of Solar Systems.** Hyperactive Io is ideal for studying planetary processes, including volcanism, tectonism, tidal dissipation, $SO_2$ atmospheric dynamics, and magnetospheric interactions.
- **Planetary Habitats.** Tidal heating driving Io's activity controls the Jovian system's habitable zone, and understanding it gives insight into potential habitats in extrasolar planetary systems.
- **Building New Worlds.** Voluminous and high-temperature volcanic and interior processes active on Io help us understand analogous very early processes on the Earth, Moon, Mercury, Venus, and Mars.

### Science Objectives and Key Measurements:

| Objectives (Gain Understanding of) | Key Measurements |
|---|---|
| A1. Io's active volcanism | High resolution repeat imaging at UV to thermal IR wavelengths |
| A2. State of Io's interior & implications for tidal heating | Measure peak lava temperature for mantle temperature & electromagnetic induction signal from mantle melt. Map/monitor global heat flow |
| B1. Nature of Io's lithosphere & unique tectonics | Image & measure topography of key tectonic structures |
| B2. Connections between Io's volcanism & its surface & atmosphere | Measure mass spectra & temporal & spatial variability of neutral species, & map spectral variations of surface |
| B3. Io's mass loss & magnetospheric interactions | Acquire in situ & remote observations of Io's exosphere, sodium cloud, & plasma torus |
| B4. Limits to active volcanism on Europa | Distant repeat imaging to search for plumes or surface changes |
| C1. Jupiter system science | Observe Jupiter, rings, moons, & magnetosphere |

*These 50-m/pixel images from Galileo reveal a lava lake in 100-m-deep Radegast Patera (L) and landslides (R) from 9-km-high Tohil Mons (center). IVO will provide >100 times more coverage at ≤50 m/pixel than Galileo.*

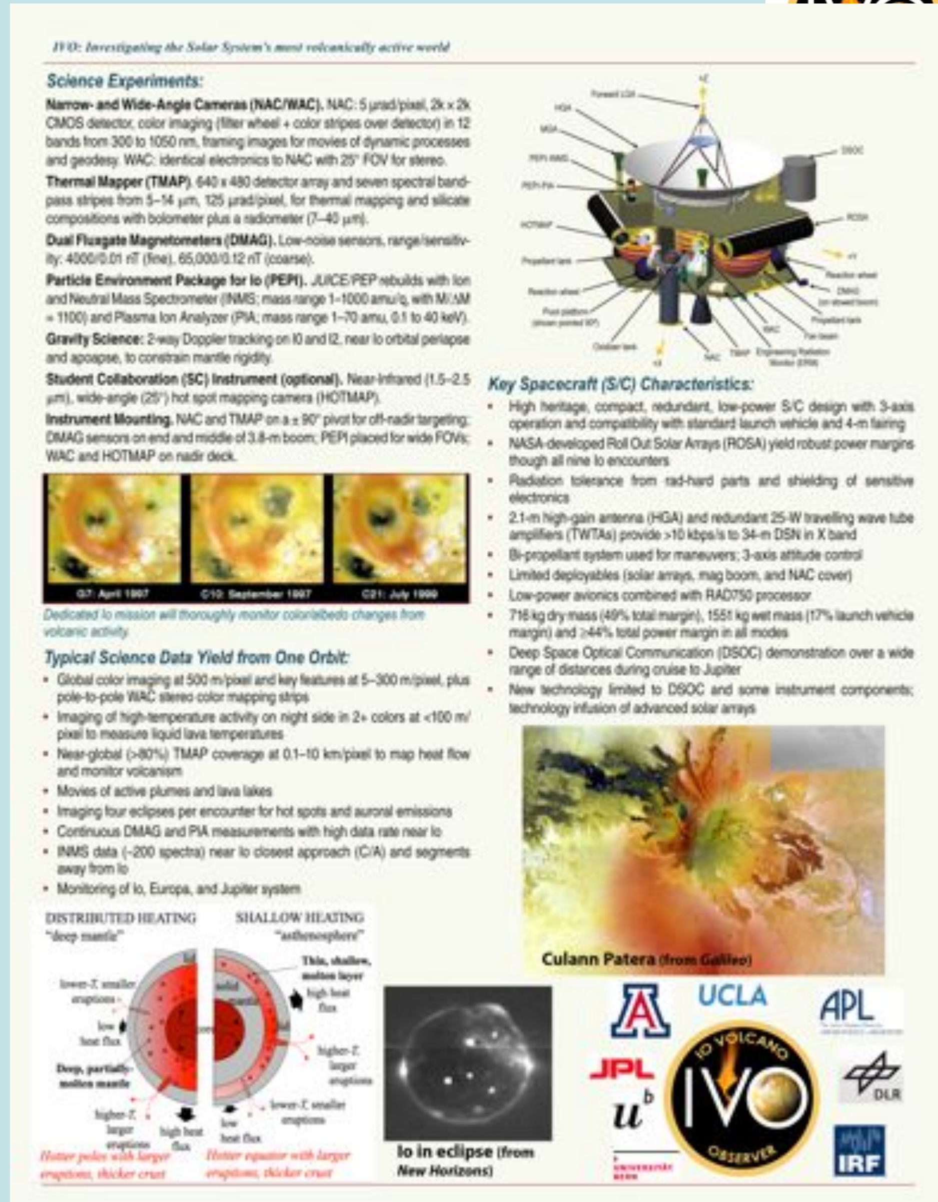
*Io presents a rich array of interconnected orbital, geophysical, atmospheric, and plasma phenomena. It is a bold, yet entirely reachable, new target for the Discovery Program.*

### Mission Overview:

- Launch May 29, 2021
- ΔV-EGA (Earth gravity assist) trajectory, asteroid flyby opportunities
- Jupiter orbit insertion (JOI) in February 2026 with 500 km Io encounter (I0) and capture into orbit inclined 42° relative to Jupiter's equator
- Eight additional Io encounters over 22 months with high-resolution views of active volcanism in daylight and darkness
- Four of the encounters are designed for optimal measurement of induced magnetic signature from mantle melt
- Mission design minimizes total ionizing radiation dose (372 krad at 100 mil Al, design margin of 2), <10% of that experienced by *Galileo*
- Collect 20 Gb science data per encounter; 100 times the Io data from the 8-year *Galileo* tour; playback near apoapsis
- Encounters last ~1 week, including global monitoring and four Io eclipses
- Nearly polar approach to and departure from Io is ideal for study of polar regions, key to testing tidal heating models

| Io Encounter Number | I0 | I1 | I2 | I3 | I4 | I5 | I6 | I7 | I8 |
|---|---|---|---|---|---|---|---|---|---|
| Days since last encounter | 0.0 | 180.4 | 81.4 | 49.5 | 61.5 | 61.4 | 61.4 | 58.4 | 52.0 |
| Closest approach altitude (km) | 510 | 500 | 500 | 500 | 500 | 500 | 500 | 400 | 200 |

*IVO's inclined orbit is optimal for key science objectives and results in a much lower Total Ionizing Dose than other Jupiter orbiters.*



*IVO: Investigating the Solar System's most volcanically active world*

### Science Experiments:

**Narrow- and Wide-Angle Cameras (NAC/WAC).** NAC: 5 μrad/pixel, 2k x 2k CMOS detector, color imaging (filter wheel + color stripes over detector) in 12 bands from 300 to 1050 nm, framing images for movies of dynamic processes and geodesy. WAC: identical electronics to NAC with 25° FOV for stereo.

**Thermal Mapper (TMAP).** 640 x 480 detector array and seven spectral band-pass stripes from 5–14 μm, 125 μrad/pixel, for thermal mapping and silicate compositions with bolometer plus a radiometer (7–40 μm).

**Dual Fluxgate Magnetometers (DMAG).** Low-noise sensors, range/sensitivity: 4000/0.01 nT (fine), 65,000/0.12 nT (coarse).

**Particle Environment Package for Io (PEPI).** *JUICE/PEP* rebuilds with Ion and Neutral Mass Spectrometer (INMS; mass range 1–1000 amu/q, with M/ΔM = 1100) and Plasma Ion Analyzer (PIA; mass range 1–70 amu, 0.1 to 40 keV).

**Gravity Science:** 2-way Doppler tracking on I0 and I2, near Io orbital periapse and apoapse, to constrain mantle rigidity.

**Student Collaboration (SC) Instrument (optional).** Near-Infrared (1.5–2.5 μm), wide-angle (25°) hot spot mapping camera (HOTMAP).

**Instrument Mounting.** NAC and TMAP on a ± 90° pivot for off-nadir targeting; DMAG sensors on end and middle of 3.8-m boom; PEPI placed for wide FOVs; WAC and HOTMAP on nadir deck.

G7: April 1997 | C10: September 1997 | C21: July 1999

*Dedicated Io mission will thoroughly monitor color/albedo changes from volcanic activity*

### Typical Science Data Yield from One Orbit:

- Global color imaging at 500 m/pixel and key features at 5–300 m/pixel, plus pole-to-pole WAC stereo color mapping strips
- Imaging of high-temperature activity on night side in 2+ colors at <100 m/pixel to measure liquid lava temperatures
- Near-global (>80%) TMAP coverage at 0.1–10 km/pixel to map heat flow and monitor volcanism
- Movies of active plumes and lava lakes
- Imaging four eclipses per encounter for hot spots and auroral emissions
- Continuous DMAG and PIA measurements with high data rate near Io
- INMS data (~200 spectra) near Io closest approach (C/A) and segments away from Io
- Monitoring of Io, Europa, and Jupiter system

### Key Spacecraft (S/C) Characteristics:

- High heritage, compact, redundant, low-power S/C design with 3-axis operation and compatibility with standard launch vehicle and 4-m fairing
- NASA-developed Roll Out Solar Arrays (ROSA) yield robust power margins though all nine Io encounters
- Radiation tolerance from rad-hard parts and shielding of sensitive electronics
- 2.1-m high-gain antenna (HGA) and redundant 25-W traveling wave tube amplifiers (TWTAs) provide >10 kbps/s to 34-m DSN in X band
- Bi-propellant system used for maneuvers; 3-axis attitude control
- Limited deployables (solar arrays, mag boom, and NAC cover)
- Low-power avionics combined with RAD750 processor
- 716 kg dry mass (49% total margin), 1551 kg wet mass (17% launch vehicle margin) and ≥44% total power margin in all modes
- Deep Space Optical Communication (DSOC) demonstration over a wide range of distances during cruise to Jupiter
- New technology limited to DSOC and some instrument components; technology infusion of advanced solar arrays

Culann Patera (from Galileo)

DISTRIBUTED HEATING "deep mantle" | SHALLOW HEATING "asthenosphere"

*Hotter poles with larger eruptions, thicker crust* | *Hotter equator with larger eruptions, thicker crust*

**Io in eclipse** (from *New Horizons*)

UCLA | APL | JPL | DLR | IRF

# Thanks for listening!