New IVO focus in 2019:
Follow the Heat!

Major Partners:

University of Arizona: Science operations, student collaboration camera

JHU APL: Mission and spacecraft design, build, and management; cameras; Plasma Instrument for Magnetic Sounding (PIMS)

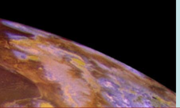
UCLA: Dual fluxgate magnetometers

JPL: Radio science, navigation

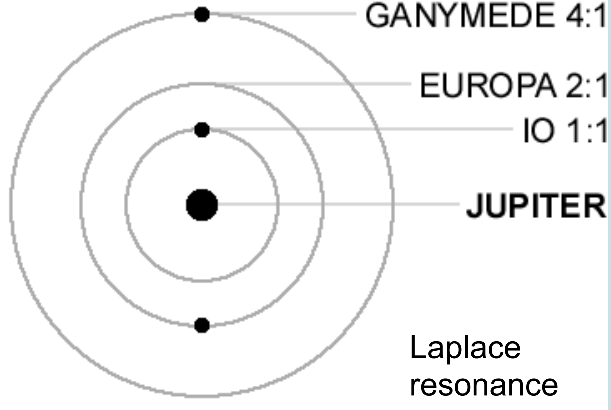
German Aerospace Center (DLR): Thermal Mapper

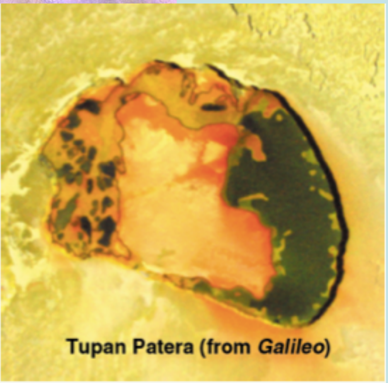
University of Bern: Ion and Neutral Mass Spectrometer (INMS)

Io is Special

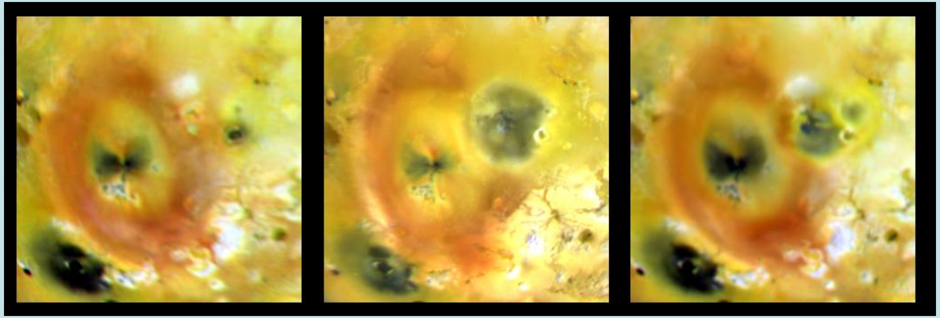


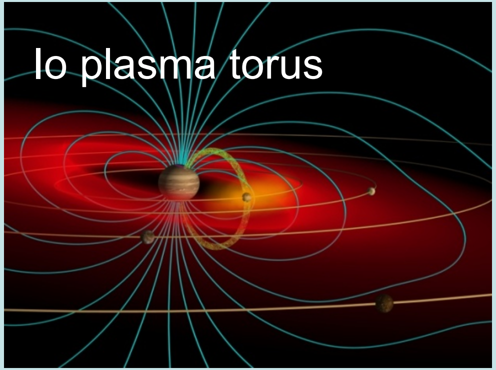
- Intense volcanism driven by tidal heating from 4:2:1 orbital resonance of Io-Europa-Ganymede
- Best place to understand the tidal heating as a fundamental planetary process
  - We can remotely measure the heat flow
- Large-scale silicate and ultramafic volcanism has been a key process on all of the terrestrial planets
  - Io is the only place in the Solar System where we can watch such voluminous and maybe ultramafic volcanism in action
- Heat-pipe tectonic end-member is relevant to early terrestrial planets and present-day exoplanets



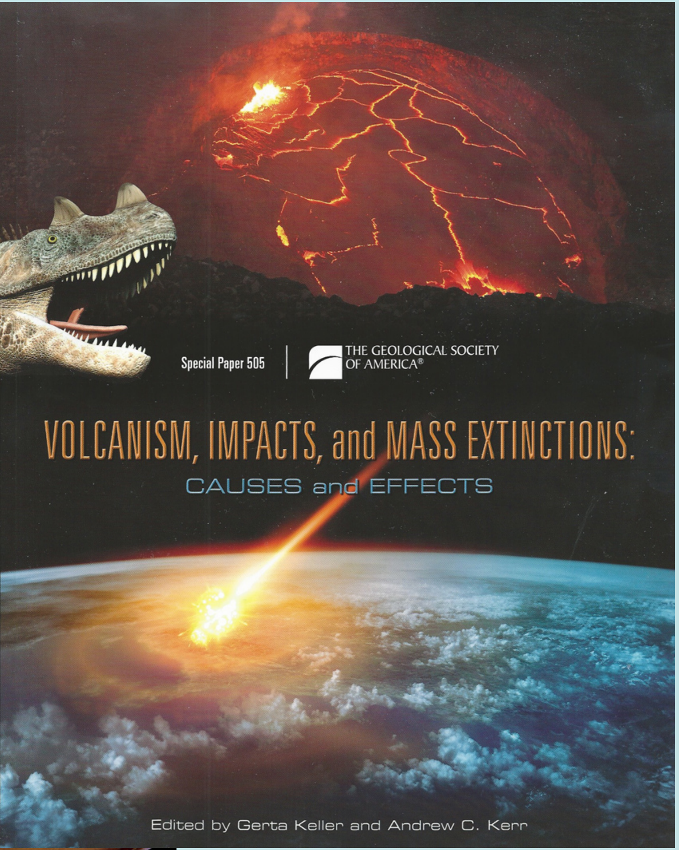


Tupan Patera (from *Galileo*)



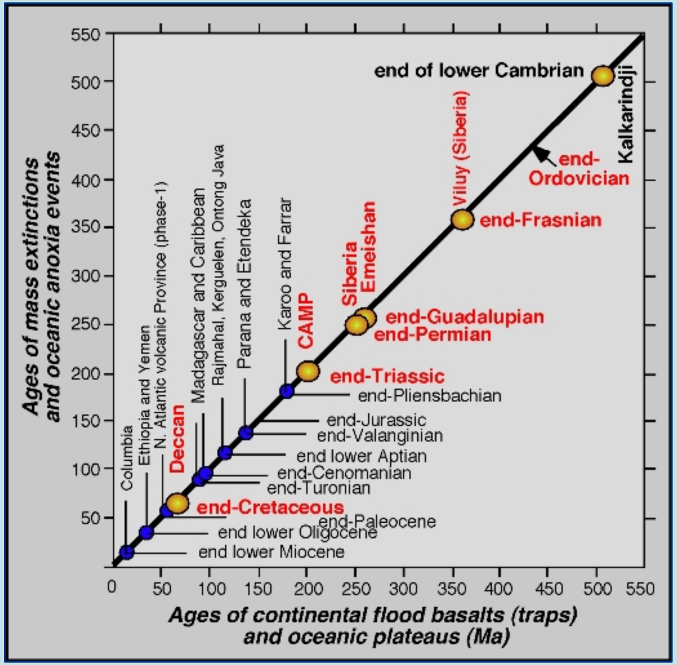


Large pulses in flood volcanism caused mass extinctions



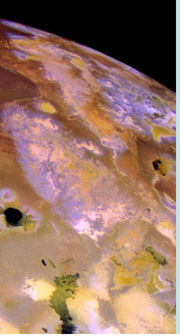
Critical advances in radiometric age dating tie major pulses in volcanism to 4 of the 5 Phanerozoic mass extinctions and to multiple other ocean anoxia events.

This close age match cannot be a coincidence!

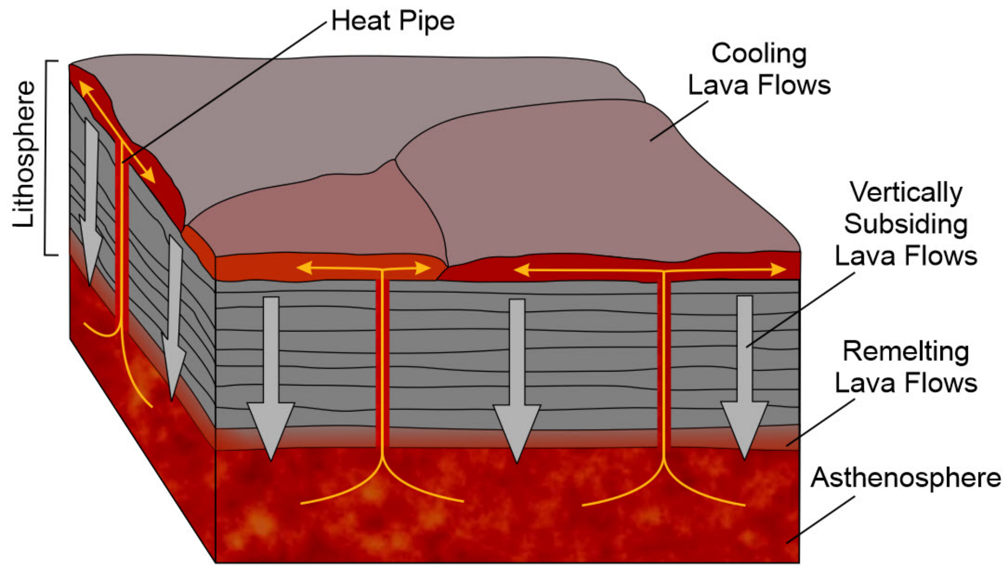


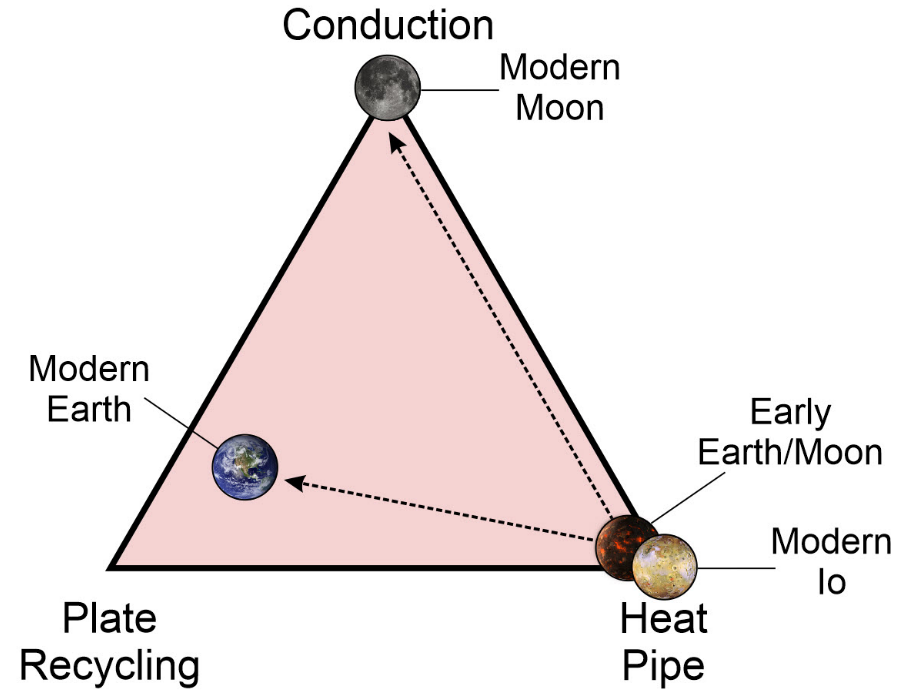
Io is the only place in the solar system where we can directly observe such high effusion rates.

The Heat Pipe end-member for how planets lose heat



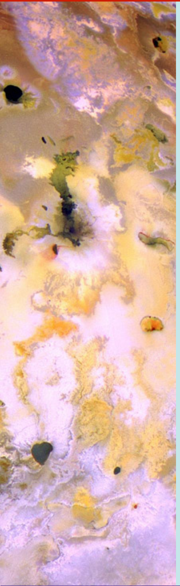
Early planetary magma oceans cool and solidify, and may lose heat primarily via heat pipes like we envision for Io today (Moore et al. papers).





Conduction cannot keep pace with subsidence rate, so lithosphere is cold and rigid

IVO will measure tidal k_2, libration amplitude, magnetic induction response, lava temperatures, and map Io's volcanism and heat flow to test four interior hypotheses.

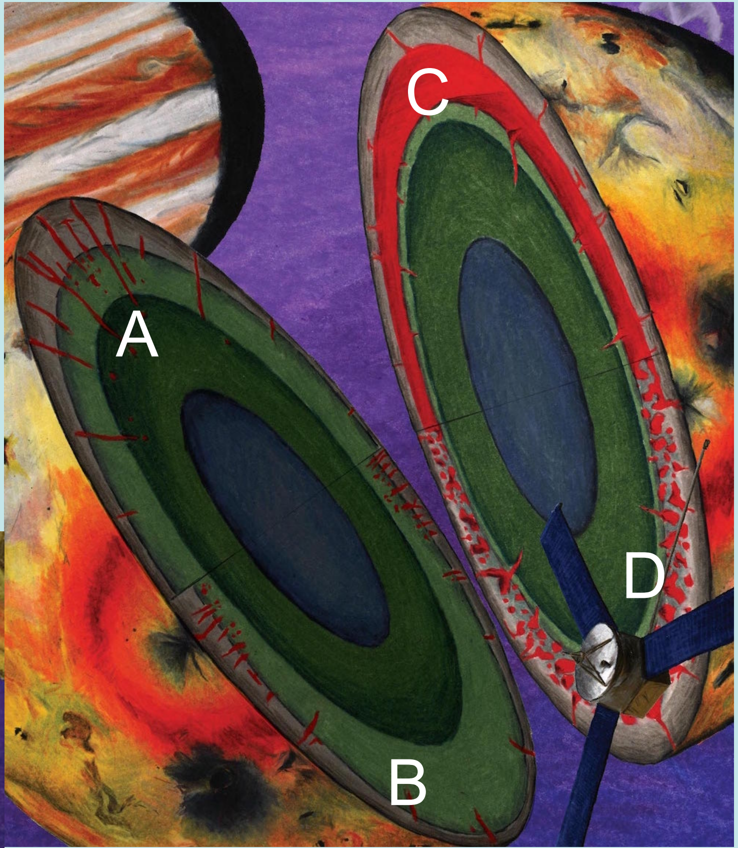


A. Solid Body Dissipation in Deep Mantle:
- Weak magnetic induction
- Polar focused volcanism
- High-T Basaltic magma
- Low k_2 and libration

and/or:

B. Solid Body Dissipation in Asthenosphere:
- Weak magnetic induction
- Low-latitude focused volcanism
- Basaltic magma
- Low k_2 and libration

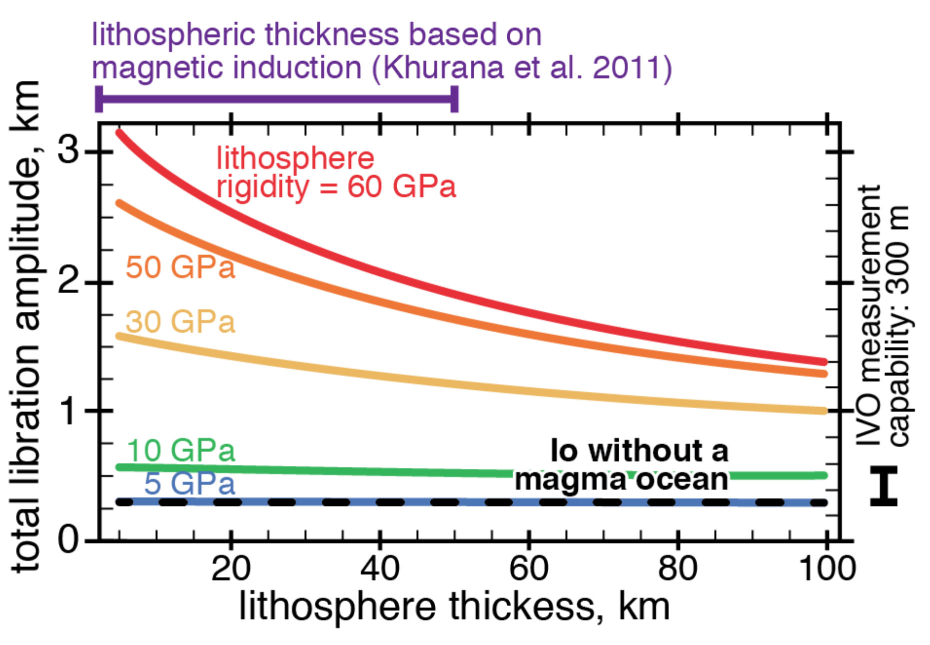
	tidal deformation:	libration amplitude:	magnetic induction:	lava temperature:	heat flow distribution:
A Solid Io, with heating in the deep mantle	low	small	weak	high-T basaltic	more polar
B Solid Io, with heating in the asthenosphere	low	small	weak	basaltic	more equatorial
C Io with a magma ocean	high	large	strong	very high-T ultramafic	more equatorial or uniform
D Io with a magma "sponge"	low	small	strong		



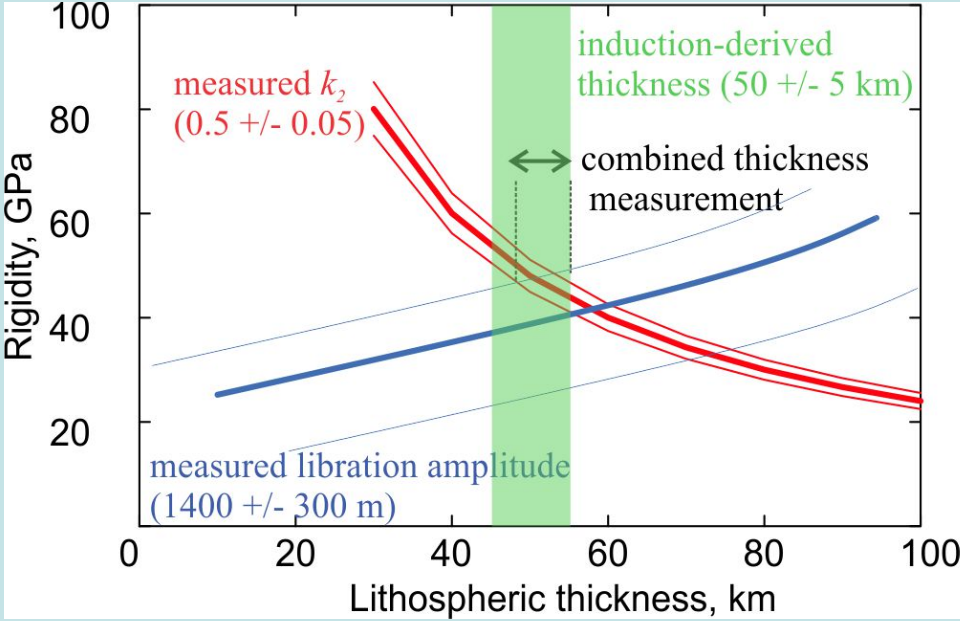
C. Fluid Body Dissipation in Magma Ocean:
- Strong magnetic induction
- Volcanism more uniform
- Very high temperature ultramafic magma
- <u>High</u> k_2 and libration

D. Fluid Dissipation in Magmatic Sponge:
- Strong magnetic induction
- Volcanism more uniform
- Very high temperature ultramafic magma
- <u>Low</u> k_2 and libration

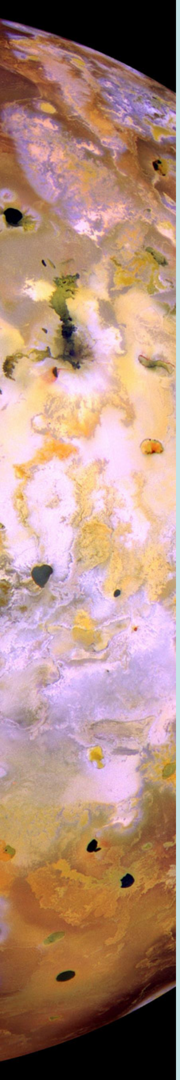
How thick and rigid is Io's lithosphere?
(Test of heat-pipe model)



Hypothetical example

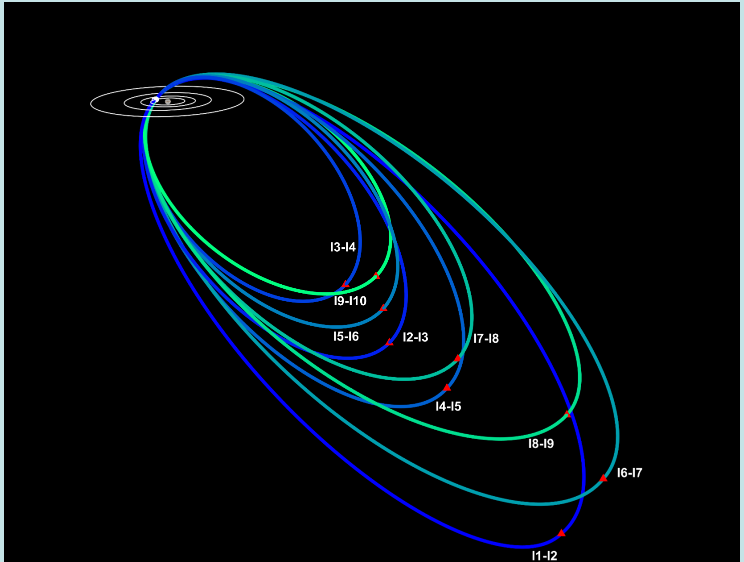


Combined measurements of k_2, libration amplitude, and lithospheric thickness from magnetic induction tightly constrain the lithosphere's thickness and rigidity. Low rigidity not expected from heat-pipe model.

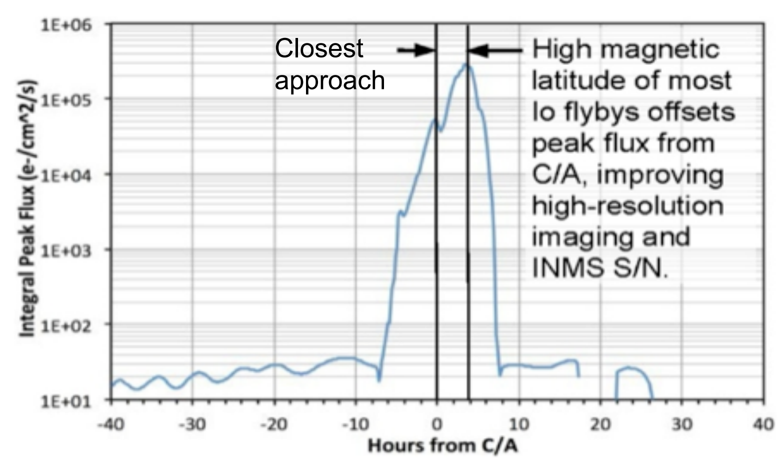


IVO Orbit optimized for science *and* to minimize total dose

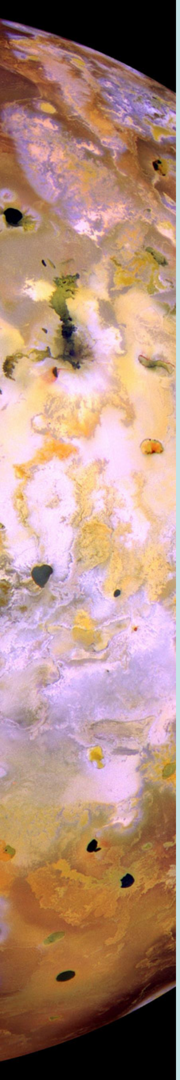
- Orbit inclined ~45º to Jupiter's orbital plane
- Nearly north-south flybys of Io has significant advantages
  - Minimizes total radiation dose per flyby
    - ~20 krad per flyby (v. ~80 for Galileo, ~70 for Europa Clipper)
    - S/C only spends ~15 hrs/flyby in the intense radiation
  - Polar observations to distinguish between tidal heating mechanisms



Ten Io encounters (I1 to I10) in nominal mission

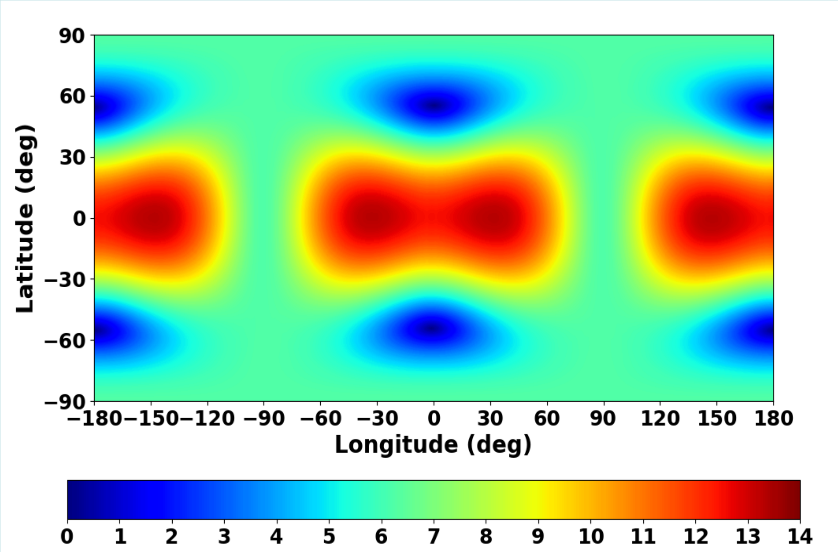


Integral peak flux (1-cm Ta equivalent shielding) is reduced by 4 orders of magnitude <10 h from C/A.

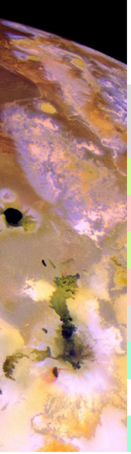


Jupiter tour to measure tidal k_2

- Must pass over the right places at the right times.
- Given IVO's orbit, this requires waiting for Io's orbit to precess.
- Need >3 yrs to measure two periapse-apoapse pairs of encounters.
  - ➢ Increases delta-v, but Mars gravity assist available in late 2020s.
- Side benefit of longet tour is that the subsolar longitude moves significantly
  - ➢ Can image >90% of Io in sunlight or Jupitershine at <300 m/pixel.



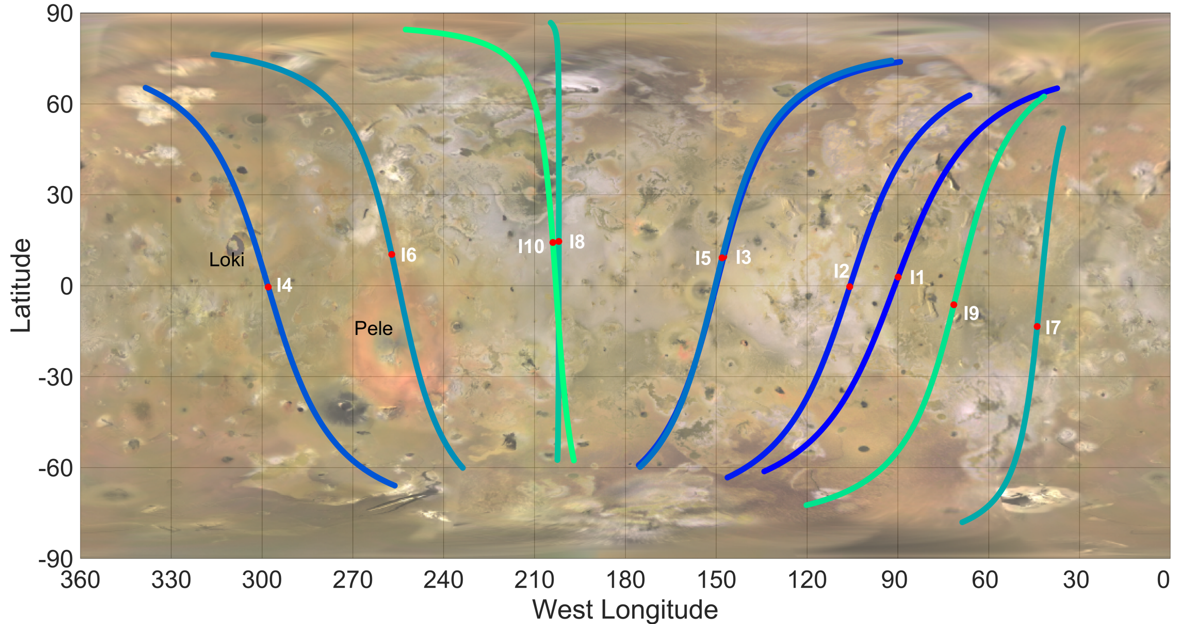
Max difference from periapse to apoapse in gravitational signal (mgals)



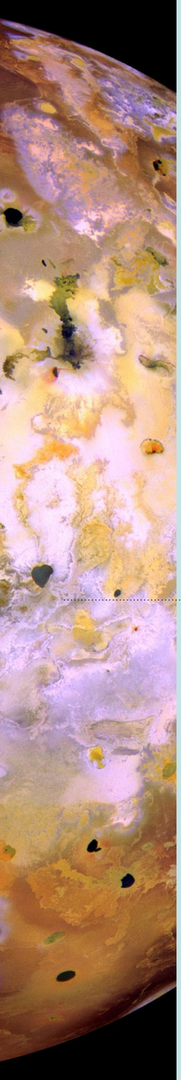
Flyby	Date (UTC)	SC Altitude (km)	Subsolar W Longitude	V_{inf} (km/s)	Magnetic Latitude of Io	True Anomaly of Io (deg)
I1	14-Dec-31	300	268.4	17.4	-7.2	132.2
I2	18-Aug-32	600	245.3	18.4	8.6	307.5
I3	30-Nov-32	300	234.7	18.8	-5.0	14.9
I4	11-Feb-33	300	227.6	19.1	8.8	63.9
I5	02-Jun-33	300	216.1	18.8	6.4	168.1
I6	02-Oct-33	201	208.6	19.1	8.2	243.9
I7	07-Jun-34	1001	186.8	18.9	-8.8	41.9
I8	21-Oct-34	301	173.8	18.6	-8.0	152.7
I9	11-May-35	300	156.9	17.6	-4.2	319.3
I10	31-Jul-35	300	149.3	17.6	-8.4	12.9

Jupiter Tour

- I1 and I2: nightside passes to reduce orbital period and map hot spots.
- I3-I5 and I8-I10: periapse/apoapse pairs over optimal locations to measure tidal k_2.
- I4 (Loki) and I6 (Pele) near true anomalies 90 and 270 for optimal measurement of libration amplitude.
- I7 is a nightside pass with optimal Jupitershine illumination to complete near-global mapping of landforms.
- I9 extends daytime mapping and is a backup orbit for libration amplitude.
- Magnetic latitudes near max values (-9.6 to +9.6) for optimal magnetic induction signature of mantle melt.
- >90% of Io mapped at <300 m/pixel in visible and <4 km/pixel in thermal IR.
- Image samples down to 2 m/pixel.



Left: flyby ground tracks over Io, color-coded by time: I1 (dark blue) to I10 (light green).
Red dot = closest approach



IVO Science Experiments

- **Narrow--Angle Camera (NAC)**
  - 10 μrad/pixel, 8 color bandpasses
  - APL, Europa Clipper
- **Dual fluxgate magnetometers (FMAG)**
  - UCLA, multi-mission heritage
- **Plasma Instrument for Magnetic Sounding (PIMS)**
  - APL, Europa Clipper
- **Thermal Mapper (TMAP)**
  - 125 μrad/pixel, 10 bandpasses from 3-14 microns plus radiometer (7-40 microns)
  - DLR, MERTIS
- **Ion and Neutral Mass Spectrometer (INMS)**
  - UBe, JUICE/PEP
- **Radio Science**
  - Tidal k_2
  - Io's orbital migration

NAC and TMAP mounted on pivot: Can always target Io with solar arrays to sun and HGA to Earth.