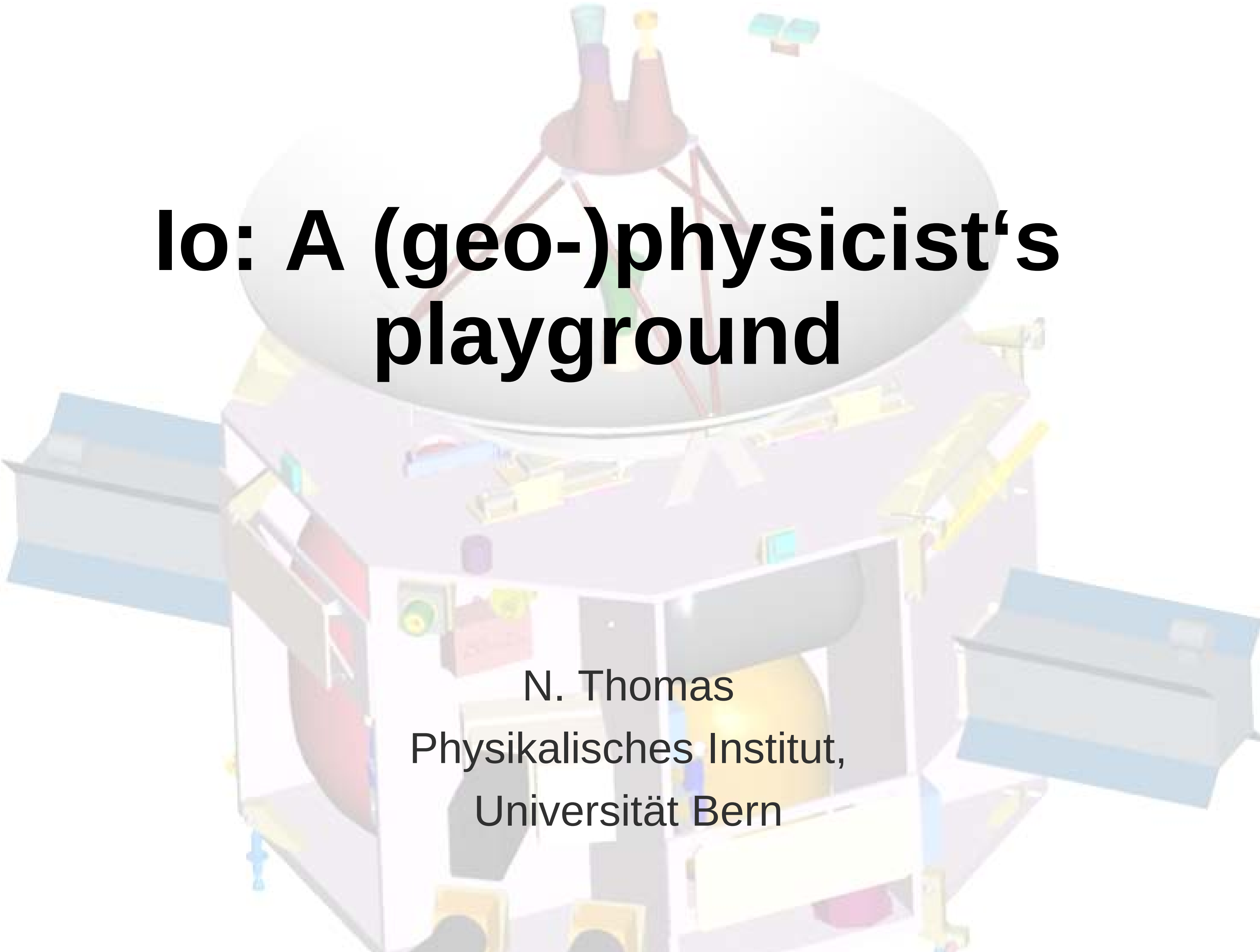
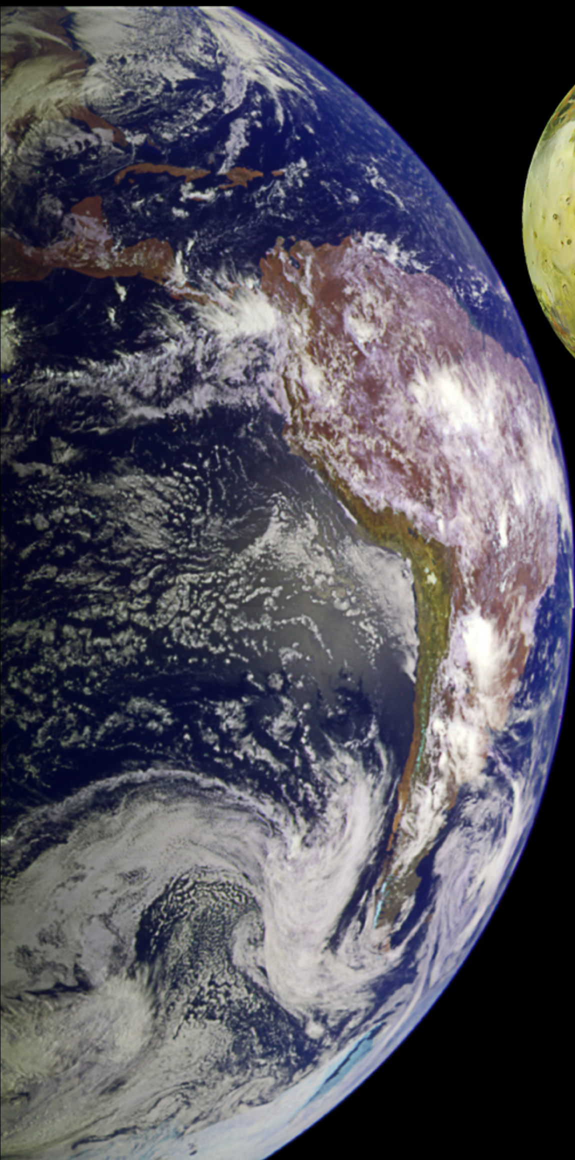
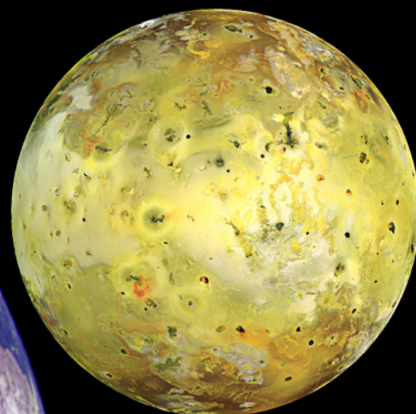


Io: A (geo-)physicist‘s playground

N. Thomas
Physikalisches Institut,
Universität Bern

Presentation Structure



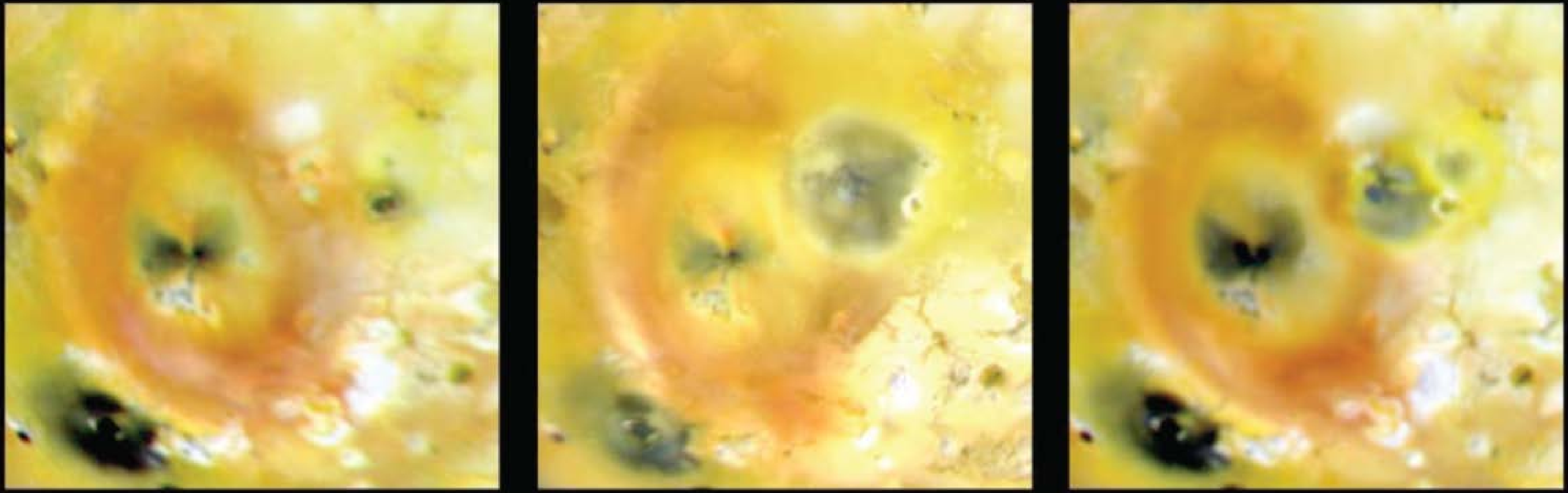


- Aim: Discussion of phenomena at Io in the context of evolution.

- Basic surface characteristics and composition
- Atmosphere and escape
- Laplace resonance
- Current evolution of the system
- Sampling the internal composition of Io
- Io Volcano Observer concept

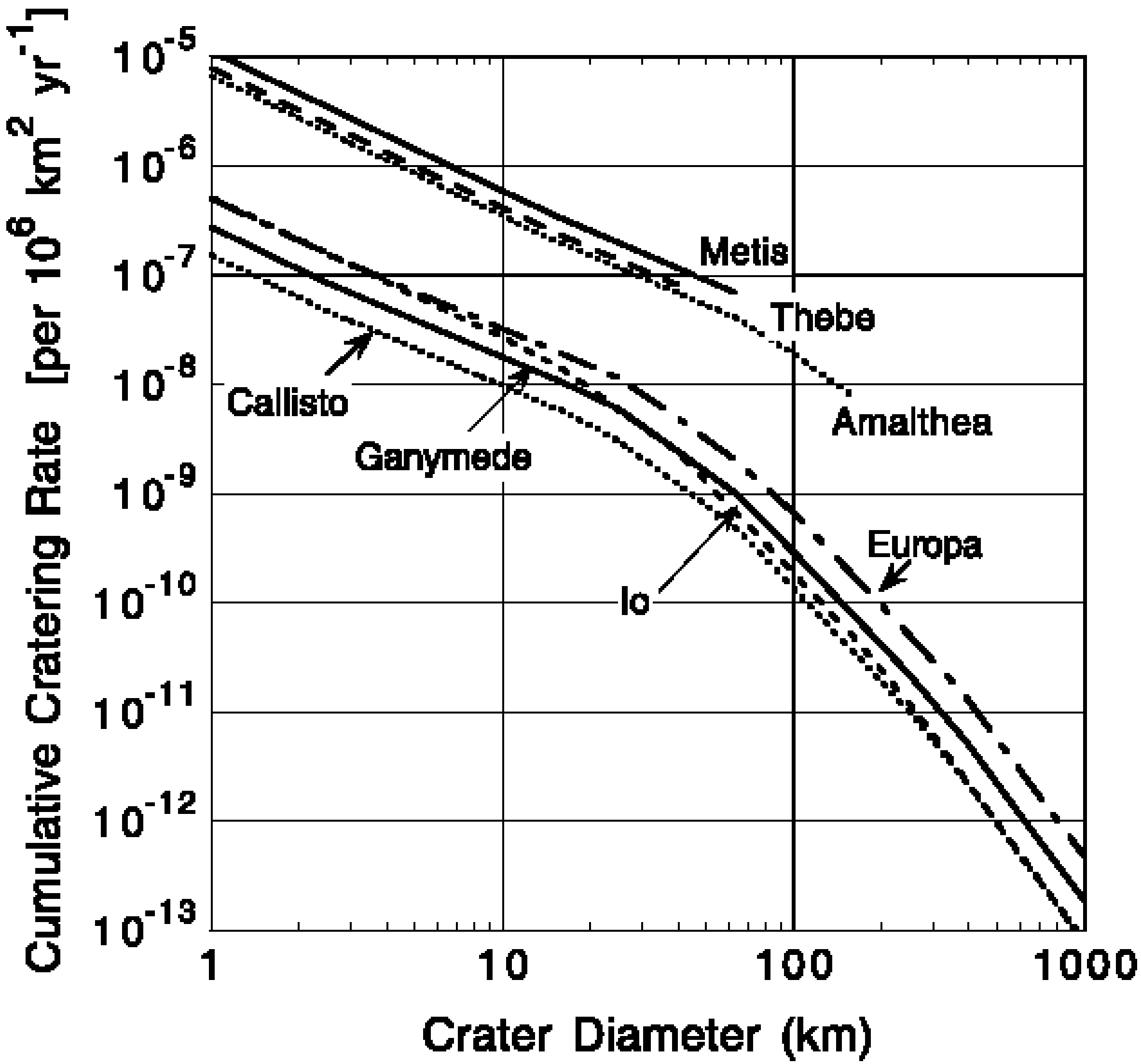
Basic Surface Characteristics

- The surface itself can tell us very little about Io's history.



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

Impact Rates in the Jupiter System



This calculation gives around 1.25, 100 km impacts every 10^7 years

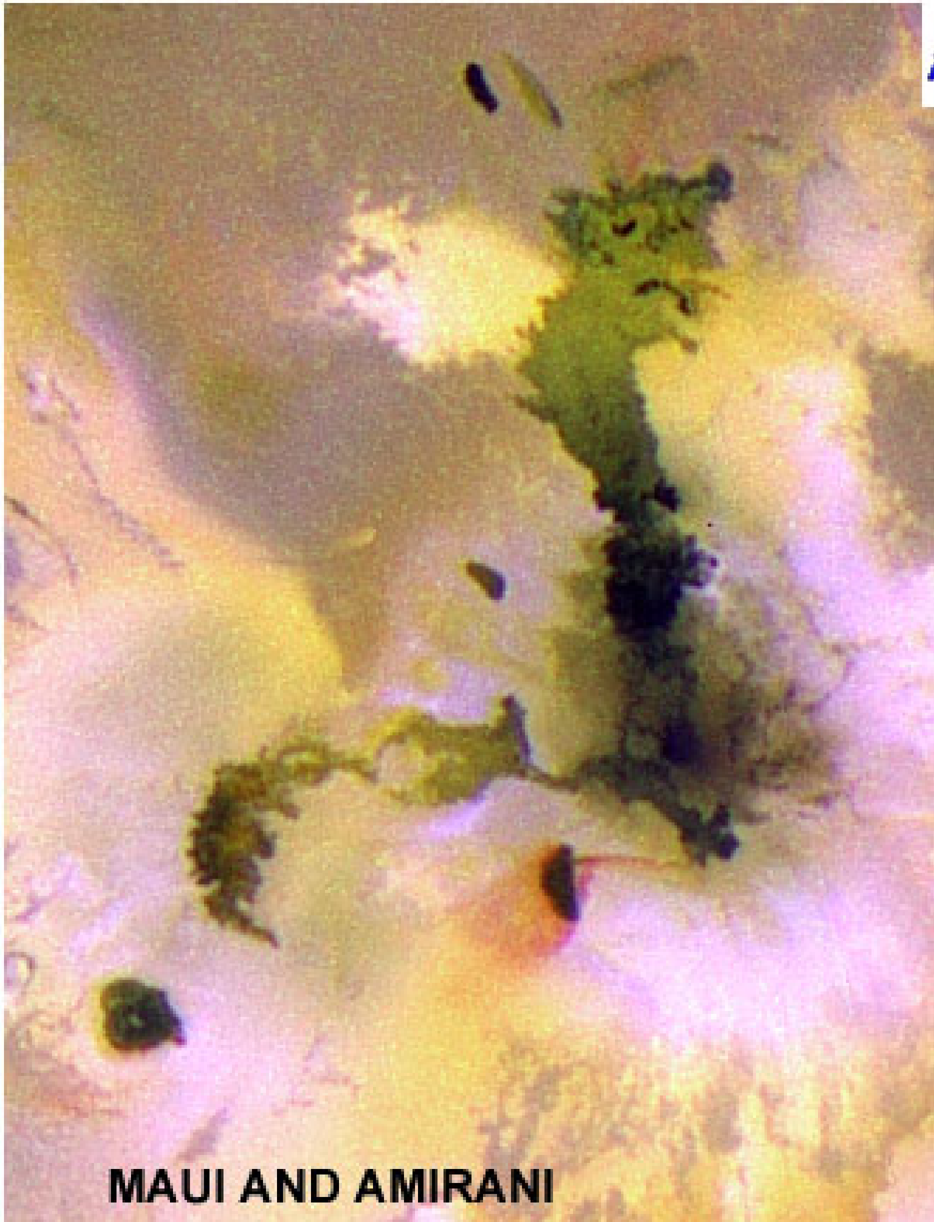
Zahnle et al., Icarus, 2003

Basic Surface Characteristics

- The surface itself can tell us very little about Io's history.

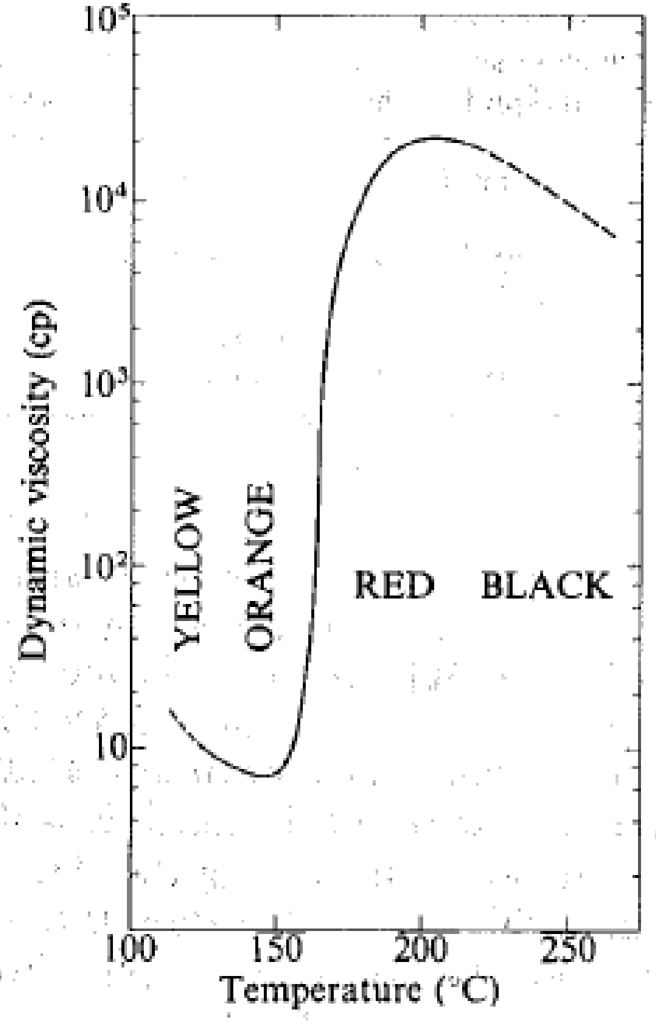
- Re-surfacing rates are estimated to be 1-10 mm year^{-1} (cf. Soderblom et al., 1979, Spencer and Schneider, 1996)
- 100 km diameter crater buried in <2 10^7 years.
- NB: 1.5-4.6% of material ejected from Io by an impact hits Ganymede.
- Sulphur/oxygen from IPT may be an even larger source (Carlson et al., 2004).

Maui-Amirani Flowfield



Credit: Laz Kestay

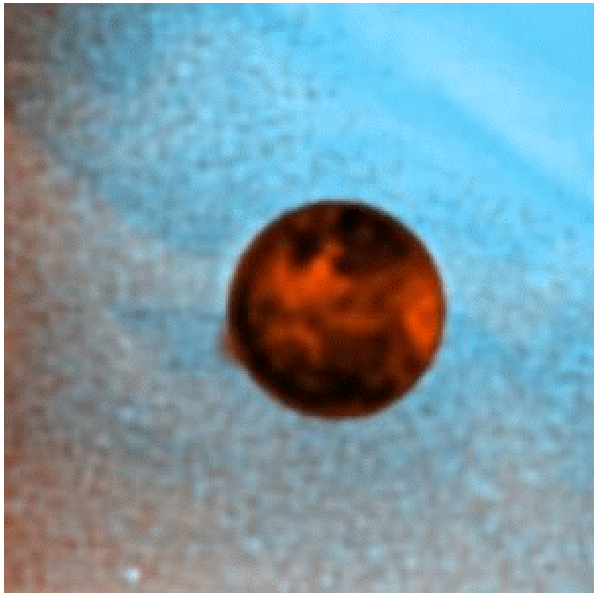
Colourful Surface



Sagan, 1979

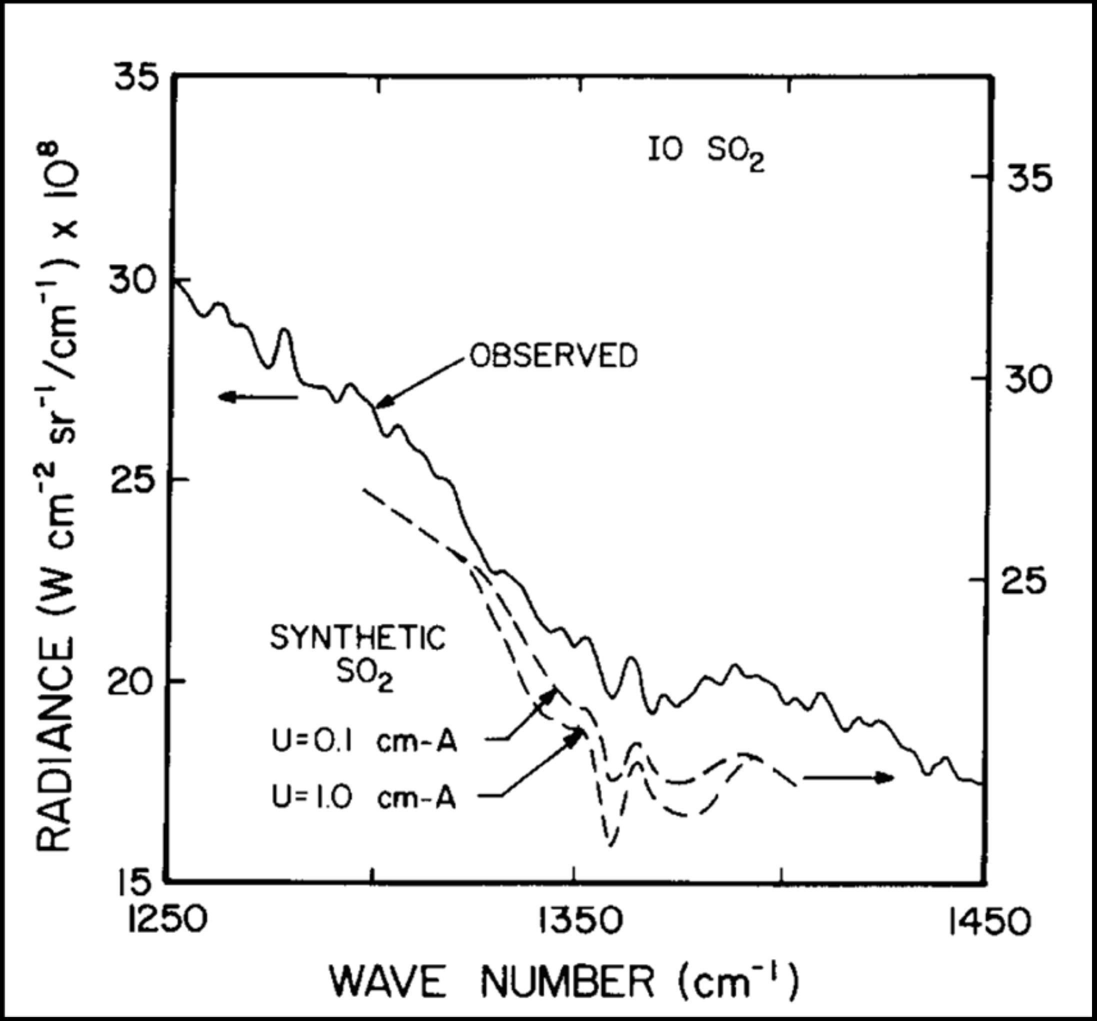
Colours indicating sulphur and its various allotropes. Some argument in the literature about purity (e.g. Kargel et al., 1999; see also McEwen et al., 2004).

S_2 detected as a gaseous species using HST.



Surface Composition

- Dominated by sulphur and compounds (SO_2).



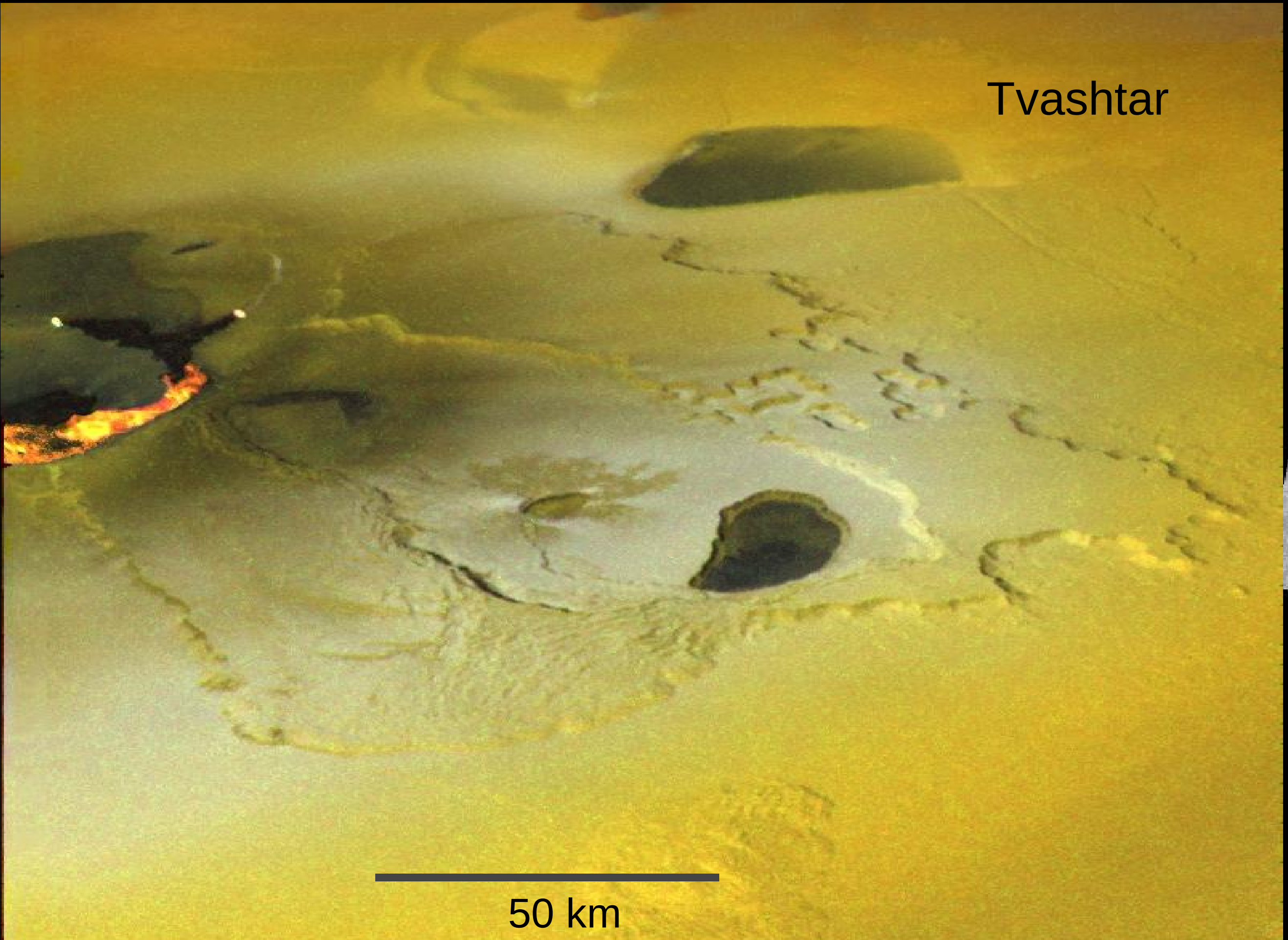
Detection of gaseous SO_2 above the surface of Io by the IRIS experiment on Voyager 2

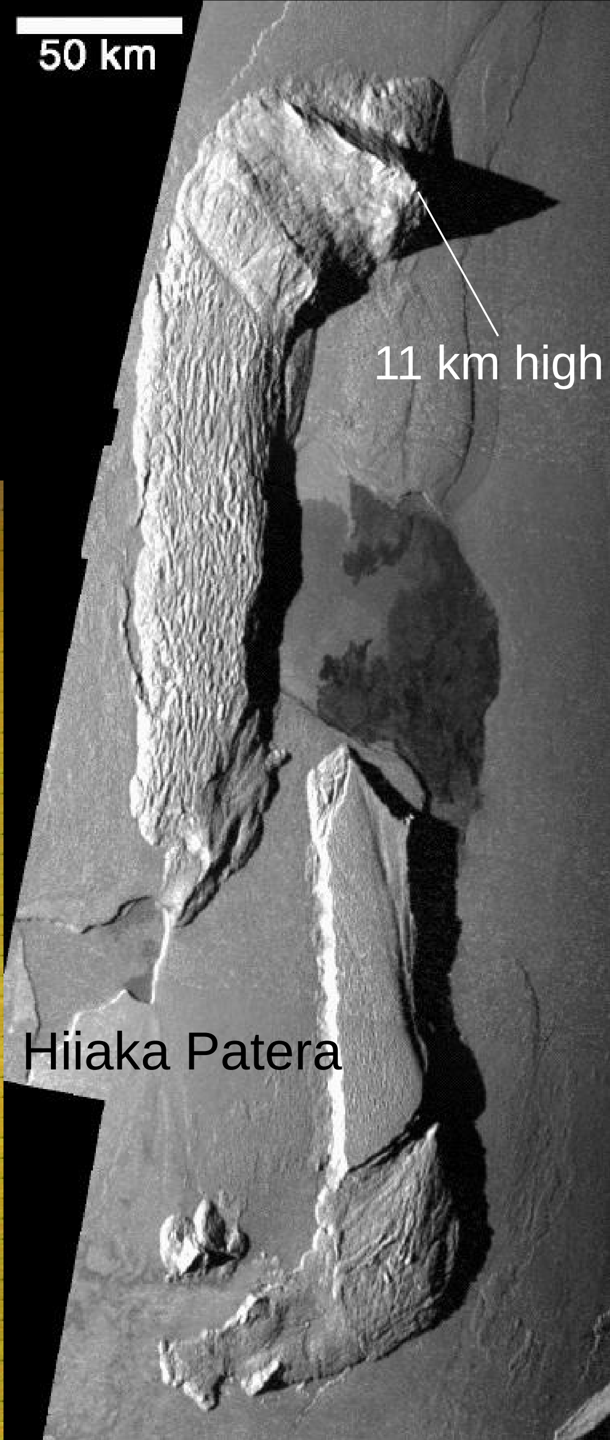
Pearl et al., 1979

Surface Composition

- Dominated by sulphur and compounds (SO_2).
- Originally silicates expected to be present (to provide structural strength; Clow and Carr, 1980)

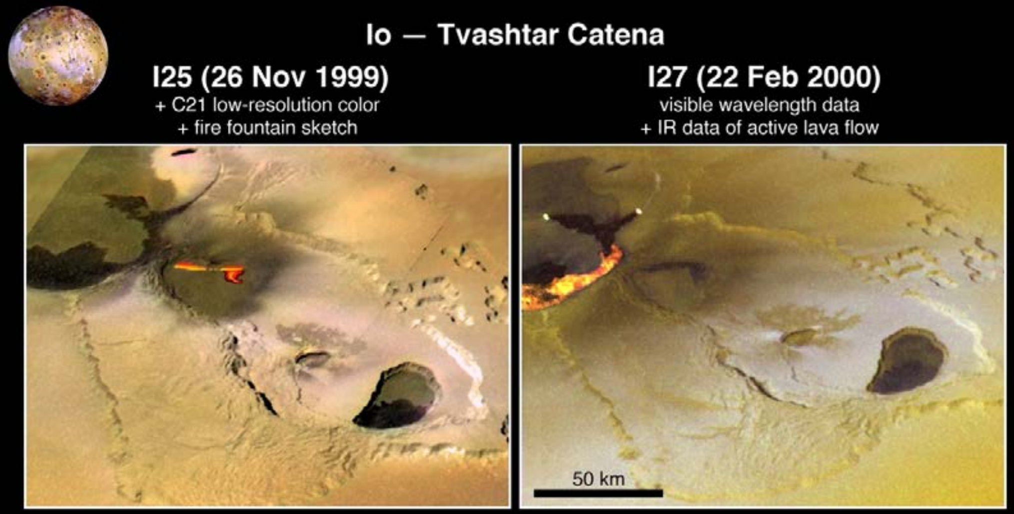
High constructs indicating structural strength - silicates





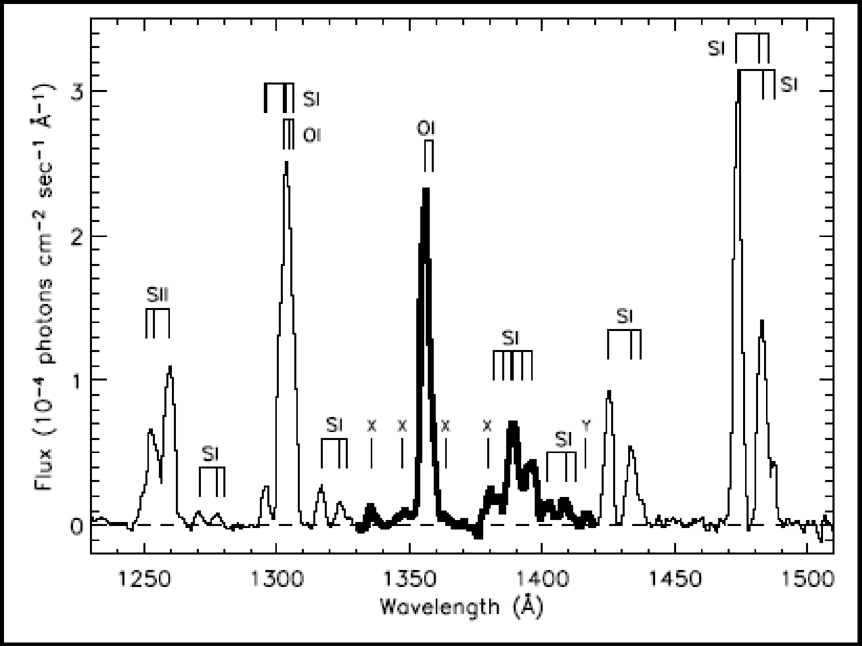
Surface Composition

- Dominated by sulphur and compounds (SO_2).
- Originally silicates expected to be present (to provide structural strength; Clow and Carr, 1980)
- Discovery of high temperature volcanism (GLL NIMS and ground-based) consistent with silicate volcanism (E.g. Davies, 2007).
- Other species inferred to be present from atmospheric and torus emissions.



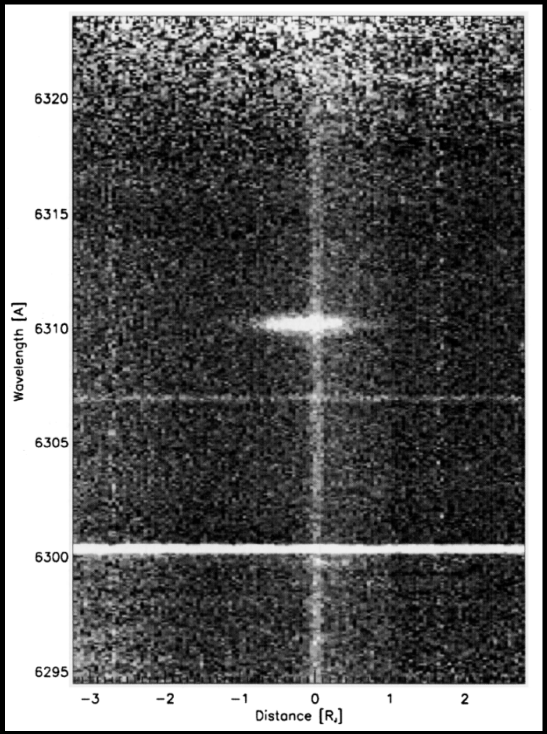

Io sodium cloud
Goldberg et al., 1984

Atmospheric and Torus Emissions

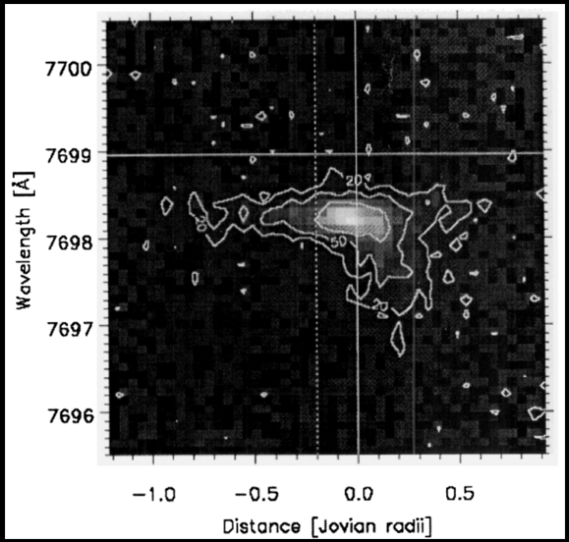


Atmospheric Cl I emission (Feaga et al., 2004) after Cl II discovered by Küppers and Schneider (GRL, 2000).

NaCl detected – other compounds likely (see Moullet et al., 2010).



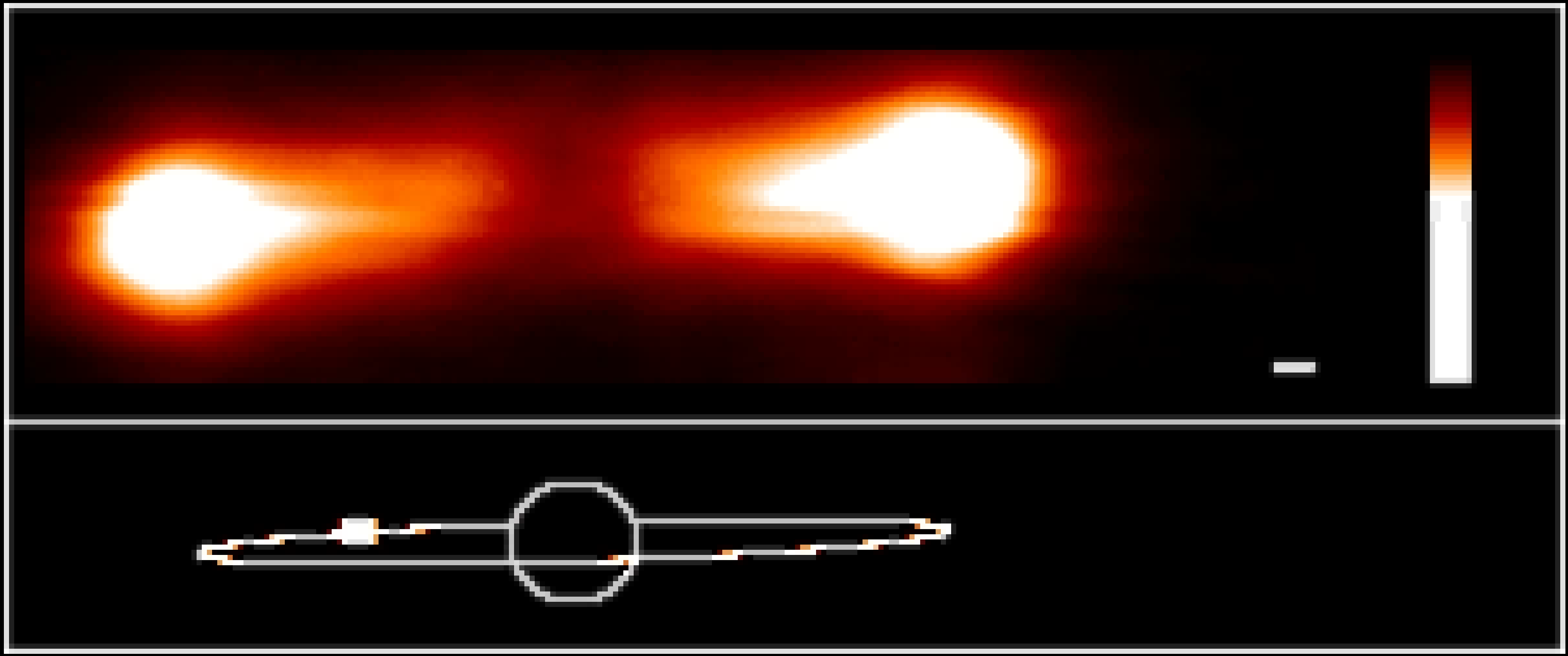
[OI] in the torus at 6300 Å

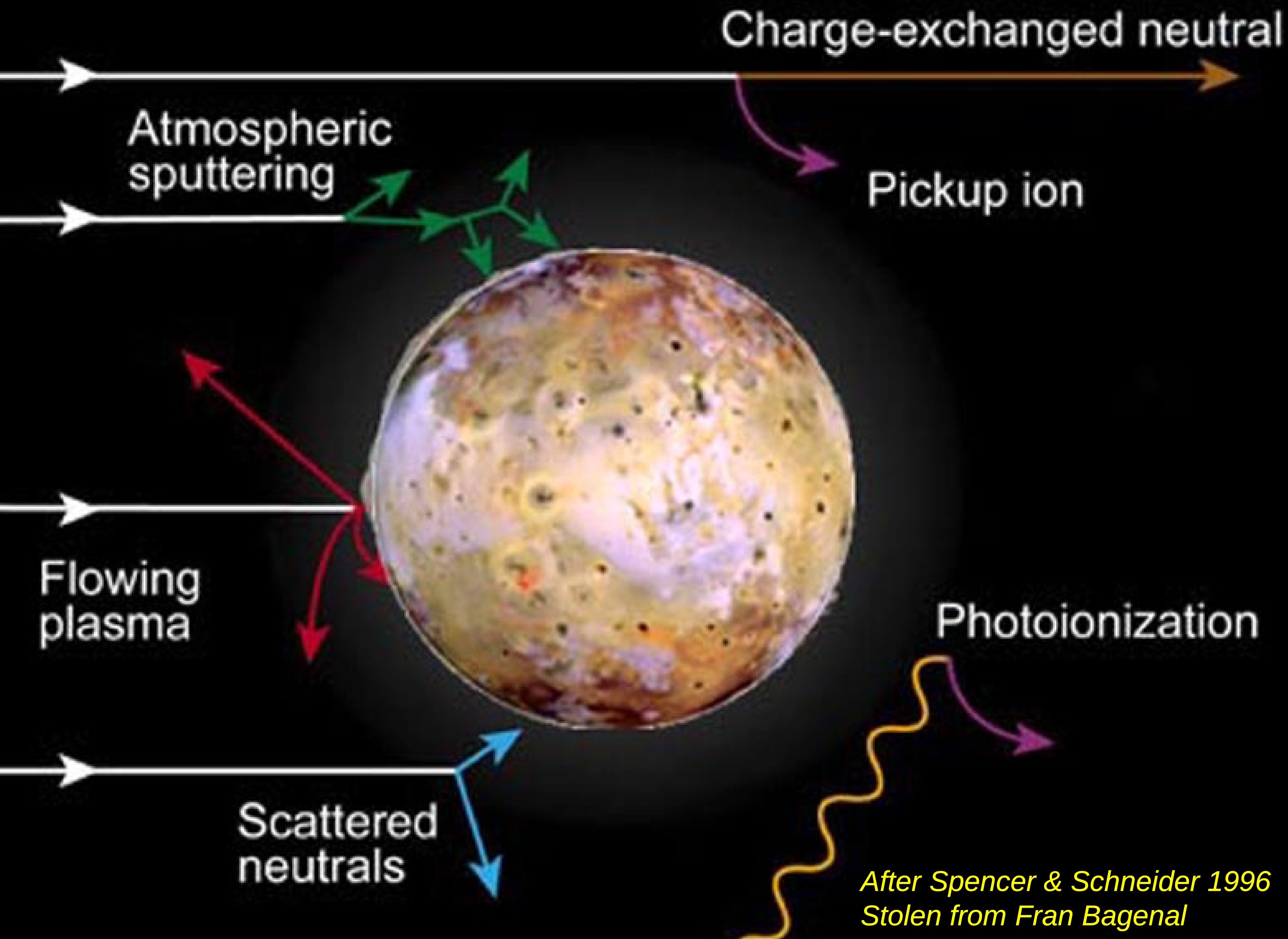


Potassium in the neutral clouds at 7699 Å

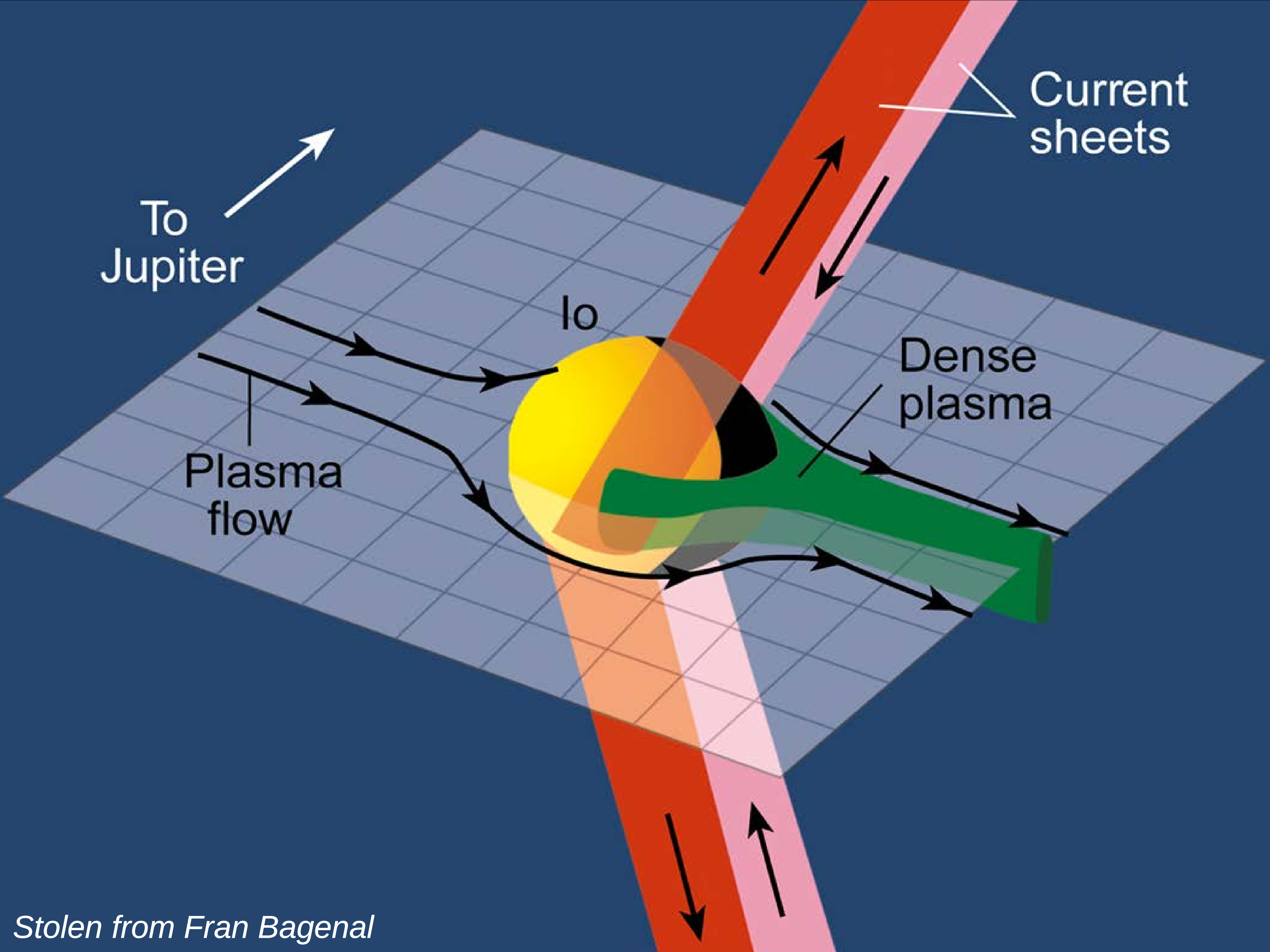
Thomas , 356 B.C.

Io Plasma Torus



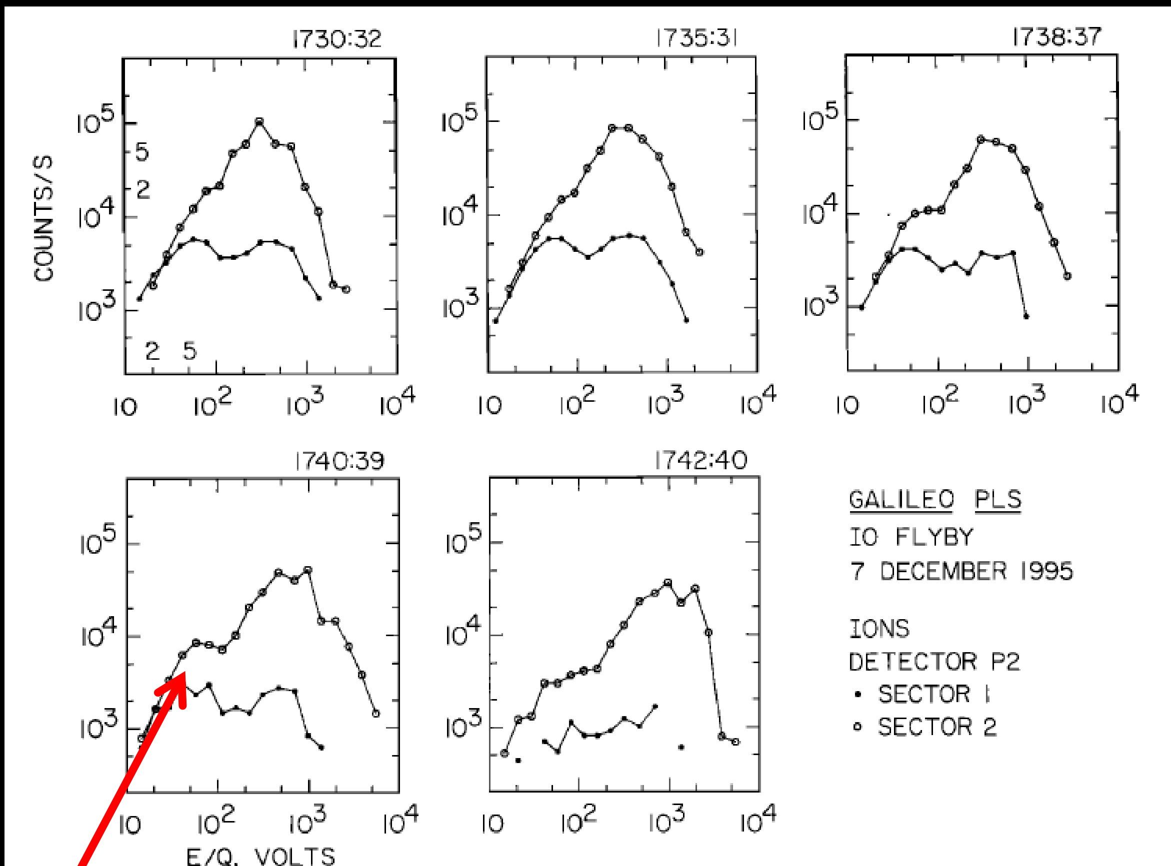


After Spencer & Schneider 1996
Stolen from Fran Bagenal



Stolen from Fran Bagenal

Hydrogen-Bearing Species



E/Q < 100 indicating protons;
Frank and Paterson, 1999

- Limited evidence of hydrogen. Some evidence of H_2S from HST.
- But NO clear evidence of water (see Carlson et al., 2007)

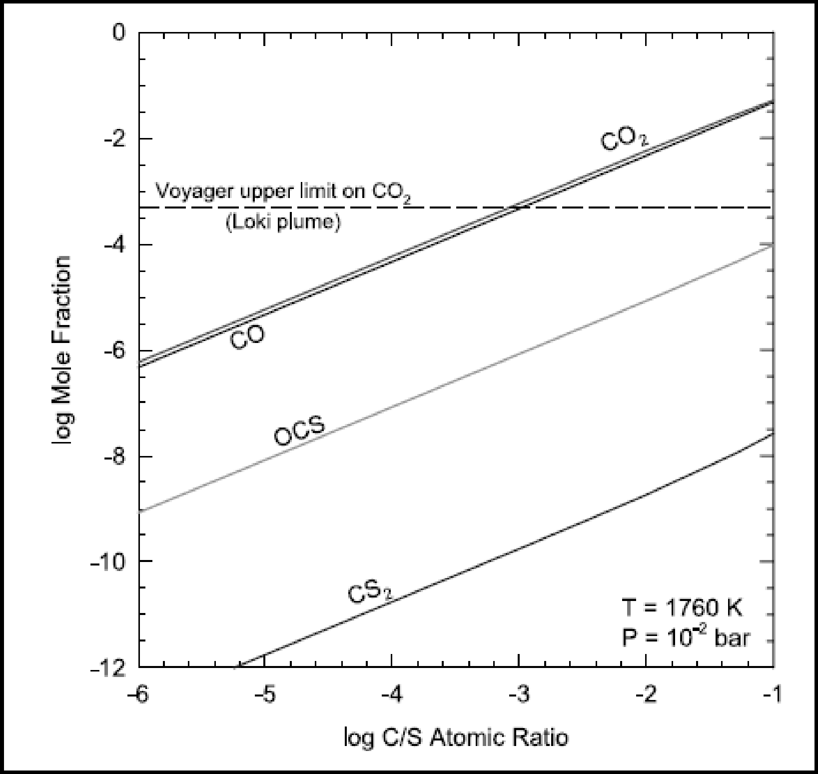
Current Mass Loss Rates

- 1 tonne/s lost at present.
- Equivalent to roughly 300 m Gyr^{-1} of loss in radius of the moon.
- Nowhere near enough to remove a water layer similar to that of Europa.

Absence of water primordial unless past conditions markedly different from today.

Carbon-Bearing Species

- Some discussion of CO_2 in 1990s (e.g. Sandford et al., Icarus, 1991) but probably faint (previously unknown) SO_2 lines.
- CO and CO_2 should be most abundant in volcanic gases (Schaefer and Fegley, ApJ, 2005)
- Upper limit on C/S of 10^{-3}
- Upper limits on CS_2 set by HST (but not actually expected on basis of chemical equil. calculations.)

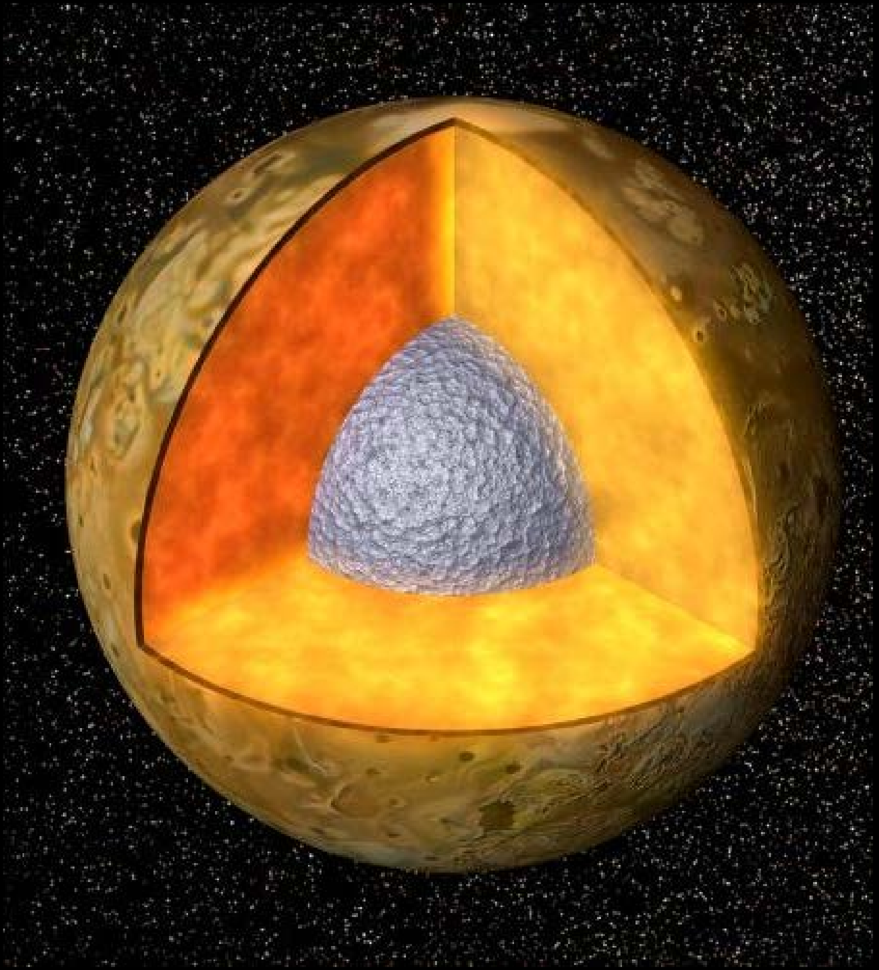


Mole fraction of carbon species as a function of the C/S atomic ratio for Pele vent conditions. CONDOR model of S+F, 2005.

Composition Summary

- We have a crude inventory of species from remote sensing.
- However, this is not really quantitative.
- Several key items missing/undetermined.

Internal Structure

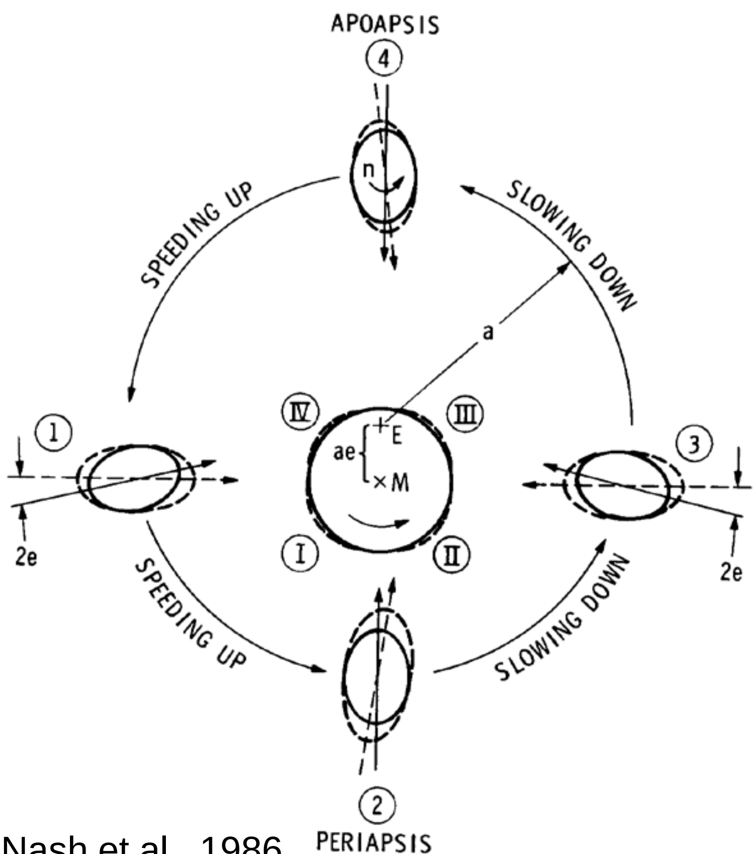


- 3.528 g/cm^3.
- Substantial Fe-rich core expected but likely to be rich in sulphur (Schubert et al., 2005).
- Size range from 650 -950 km (10-20% of Io's mass).
- Lithosphere can be thick (and probably needs to be to support topography; Turtle et al.). Simple models suggest <40 km (Moore et al., 2007).
- Heat conduction through lithosphere not a major transport mechanism – magmatic transport required.
- Not completely obvious that lithospheric composition same as underlying mantle.
- Crust "re-cycled" in < 4 10^7 yr.

Laplace Resonance

$$\lambda_I - 3\lambda_E + 2\lambda_G \approx \pi$$

λ_x = mean longitudes of the satellites Io, Europa and Ganymede



Nash et al., 1986

Europa forces Io's orbit to be eccentric leading to motion of the tidal bulge which is raised by Jupiter.

C_{22} > 50 times larger than Callisto.

Friction generates enormous quantities of heat leading to observed volcanism.

Global heat input:
2.5 W m^{-2} (Veeder et al. 1994)
0.4-1.2 W m^{-2} (Marchis et al. 2005)
For 4.5 Gyr that = 0.03% of Jupiter's rotational energy!

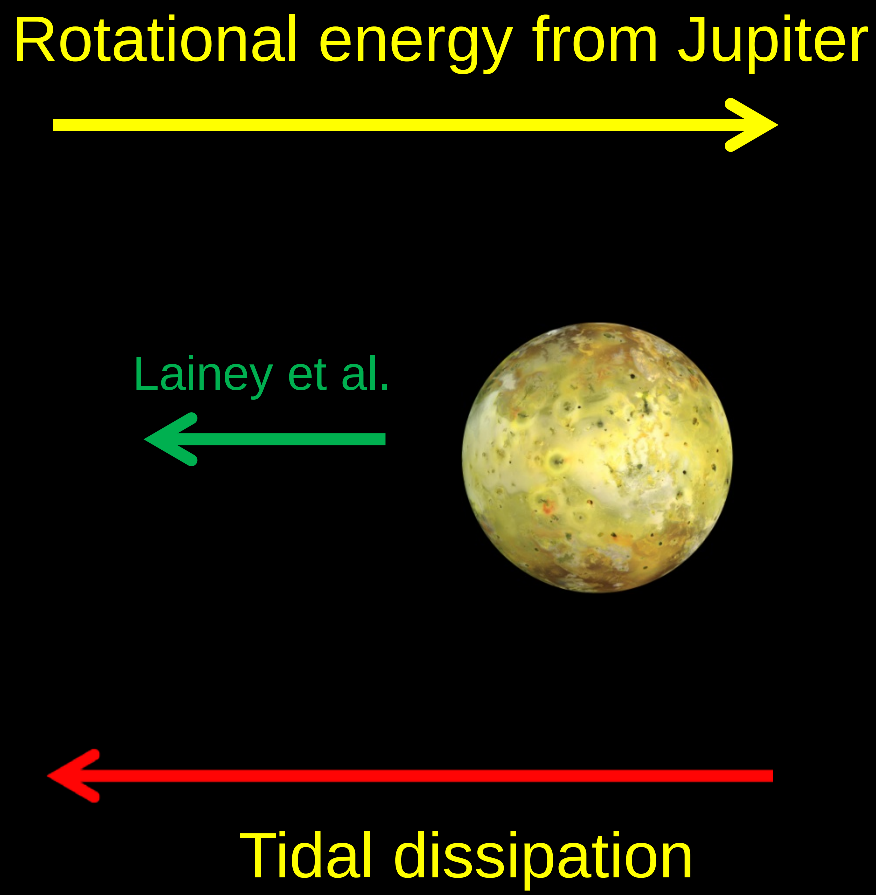
Synchronous Rotation

- Peale (1977) estimated despin timescale as
  - t_{despin} ~ 5000 x (Q/100) yr.
- Q = 10 – 500 (Goldreich and Soter, Icarus, 1966)

- Implies extremely rapid transition to synchronous rotation unless Io underwent large migration.

Is the Laplace resonance stable?

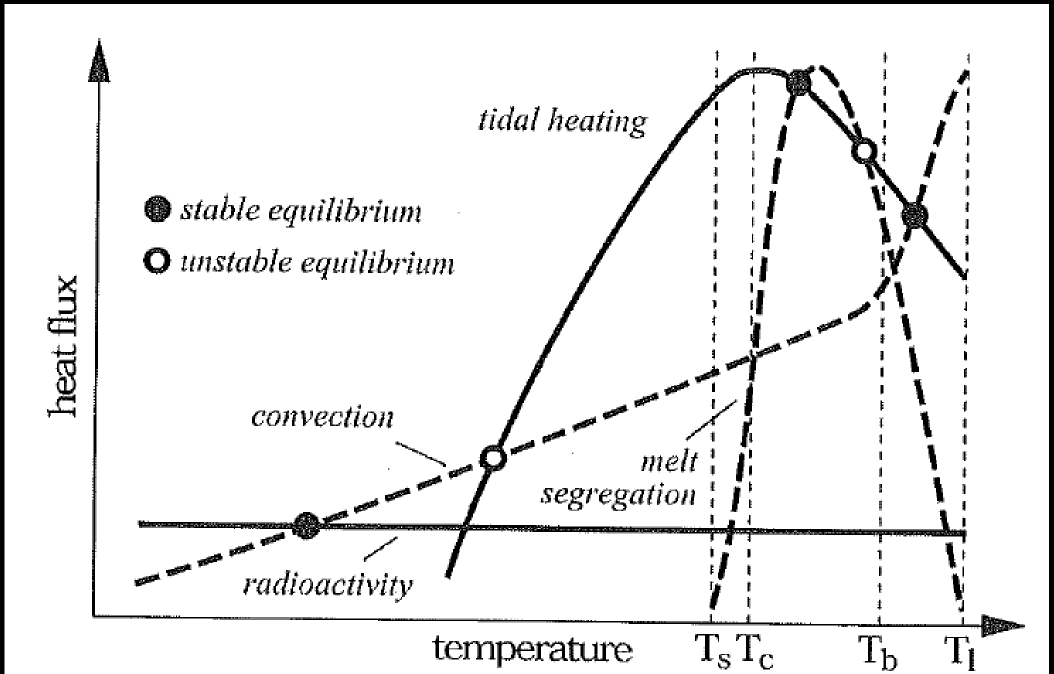
- Lainey et al., Nature, 2009 claim that the system is evolving OUT of the Laplace resonance (at the 3 sigma level).



Evolution of Tidal Heating

- Fischer and Spohn (1990) studied evolution through the Laplace resonance
  - There are multiple equilibria!
  - E.g. Frictional heating slows as solid matrix loses coherence.

Also, if dissipation reduces (because Io leaves the resonance inwards), the satellite will accelerate outwards again – back into resonance.



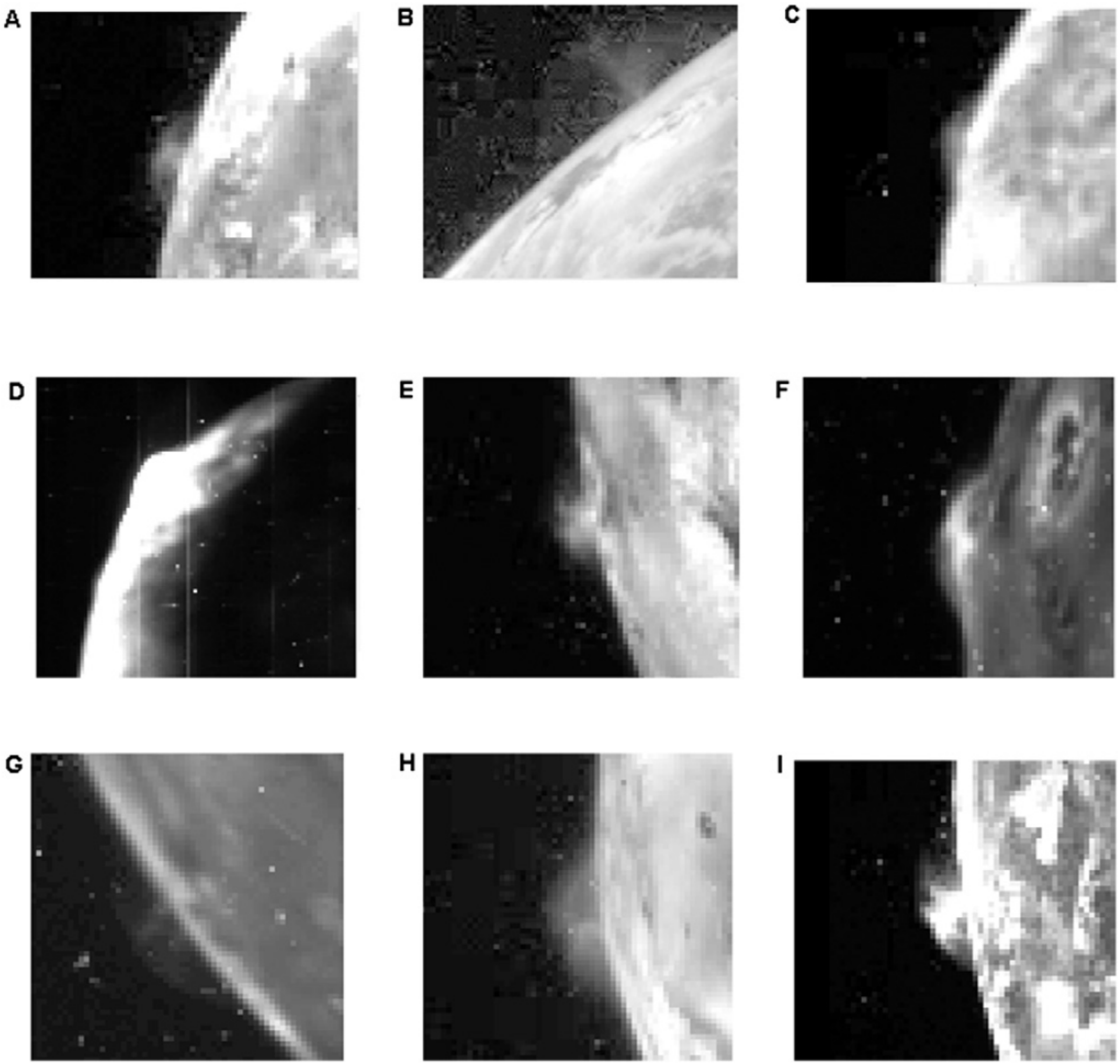
Moore et al. (2007) after Fischer and Spohn (1990)

The Fischer-Spohn Assumptions

- Three layer model with an Fe/FeS fluid core, a silicate mantle, and a thin (30 km) lithosphere.
- Few direct constraints on Io's rheology.

- But the time needed to reach the present state suggests Laplace resonance age of >0.5 Gyr.

Volcanic Plumes



Pillan

Prometheus-type plumes on Io.

Fountain-like structure, with umbrella-style canopys up to 100 km in height.

Pele-type plumes (e.g. Grian) can be >350 km in height.

Variable dust load.

Gas emissions up to much higher altitudes (see during eclipse).

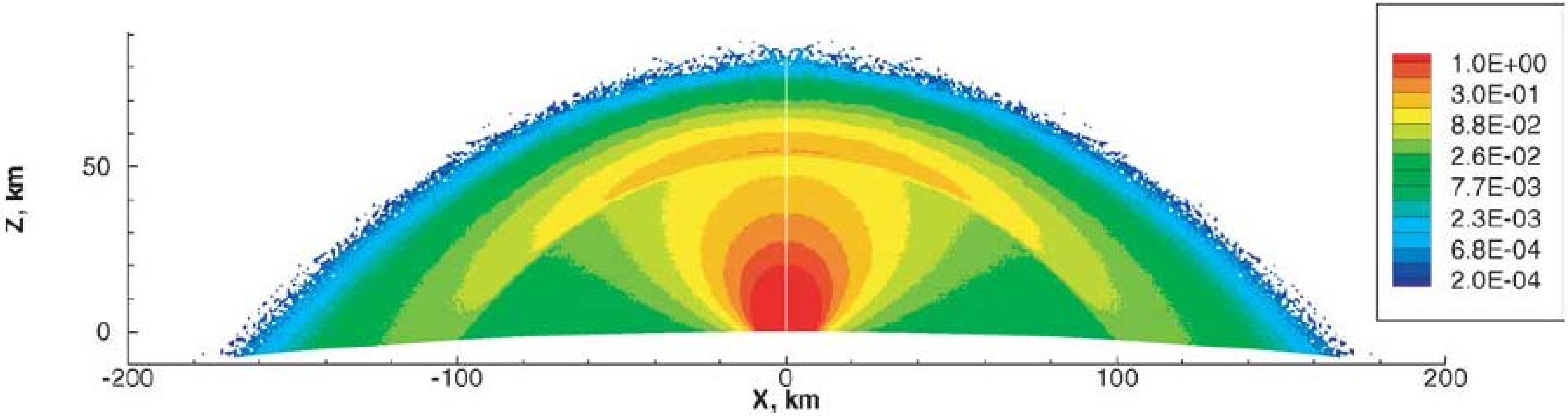
Geissler and McMillan (2010)

Volcanic Plume, Ra.

Separated by 1 hour. Out of and in eclipse.

Geissler and McMillan (2010)

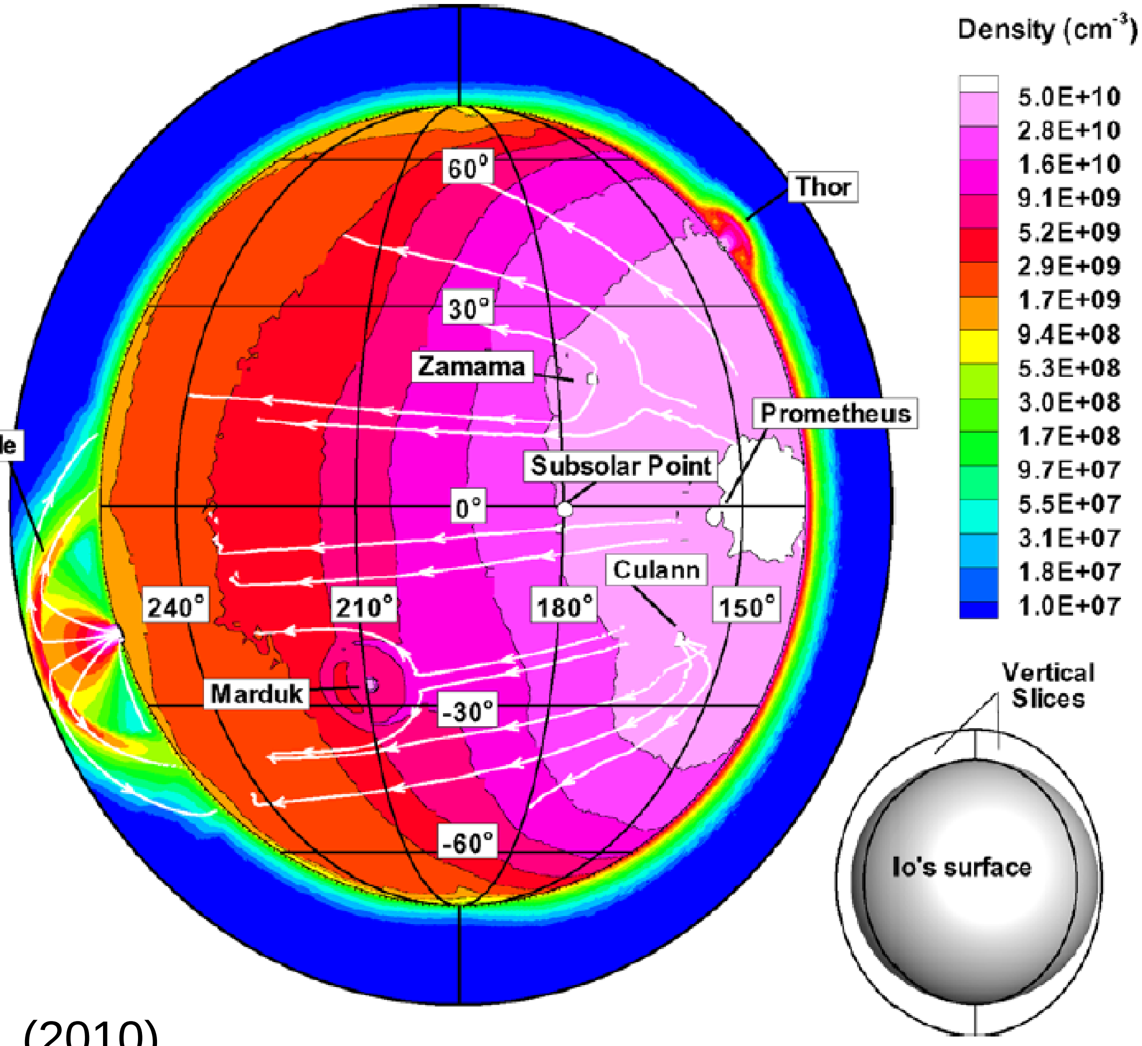
Prometheus-Type Models



Number density normalized to $5\ 10^{16}\ m^{-3}$; Zhang et al, 2004.

Particles included in other runs.

Comprehensive 3-D DSMC Model

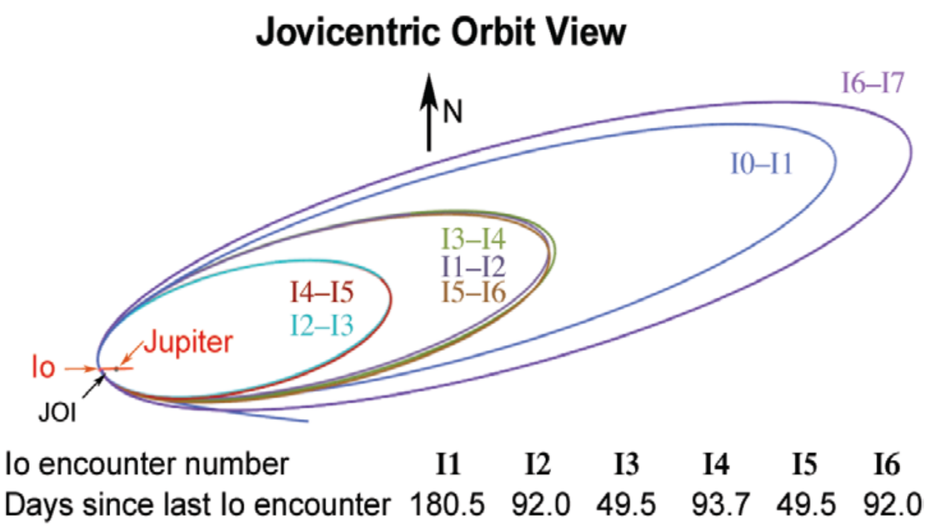


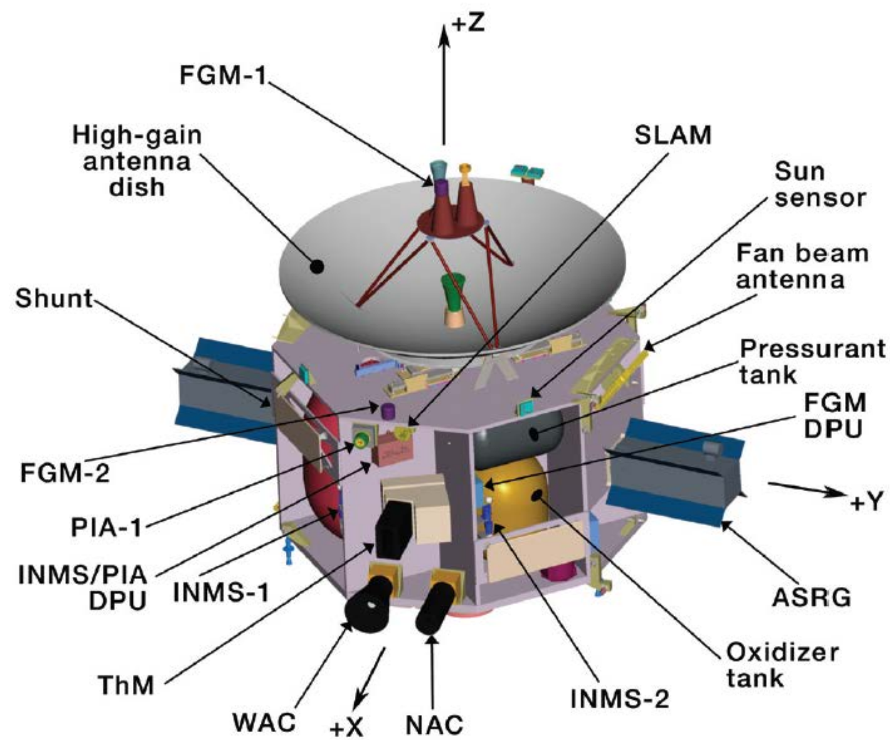
Walker et al. (2010)

Io Volcano Observer

A Discovery mission to Io

- Proposed in last Discovery round and ranked category 2.
- Details in Adams, E. et al., IEEE, 2012.





- The aim would be ultimately to fly through and sample a plume

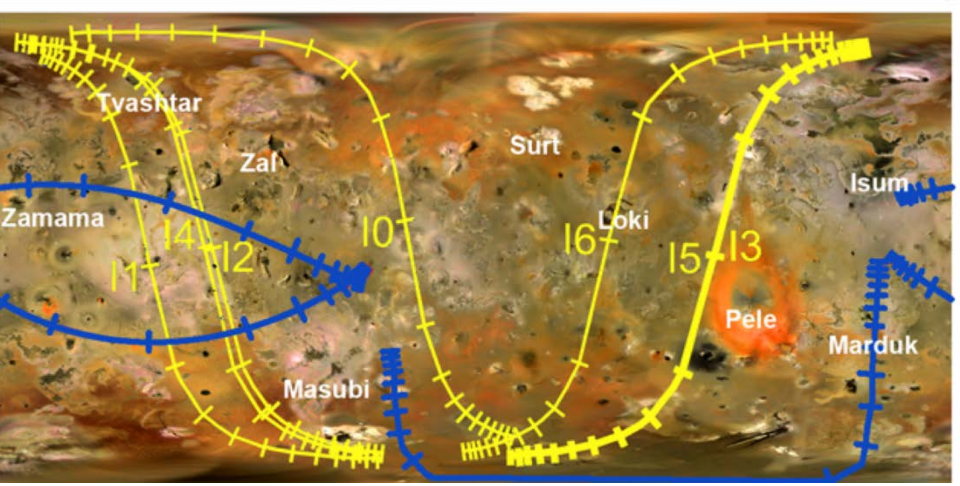
Payload Summary

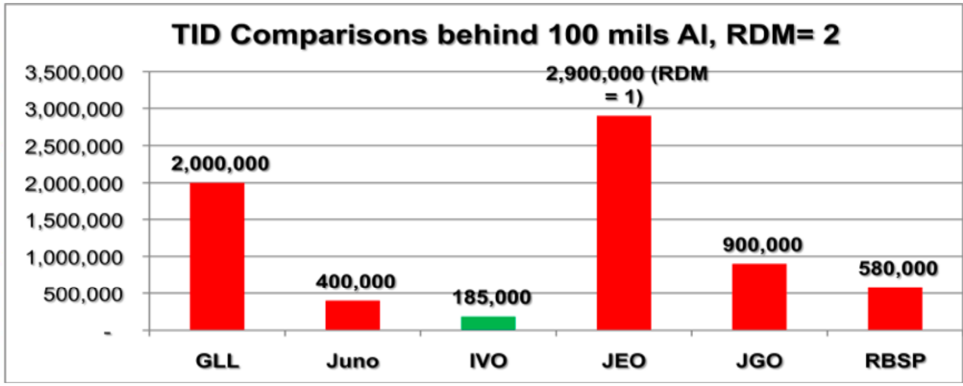
Instrument	Mass (ex. Shield) [kg]
Narrow angle camera	8.3
Wide angle camera	4.8
Ion and neutral mass spectrometer	4.3
Plasma ion analyser	0.9
Fluxgate magnetometer	2.9
Thermal mapper	8.8

IVO: Fly-bys

- **Goal:** minimize the total ionizing dose while achieving science objectives
  - I1 & I2 are nightside passes for plume & hot spot searches
  - I3 & I5 are dayside passes optimized for measurement of the induced magnetic signature from mantle melt
  - I4 is a 178-km alt flyby optimized for surface composition measurements by INMS & hot spot observations
  - I6 is a 200-km alt flyby over the Loki Patera

Adams et al. (2012)

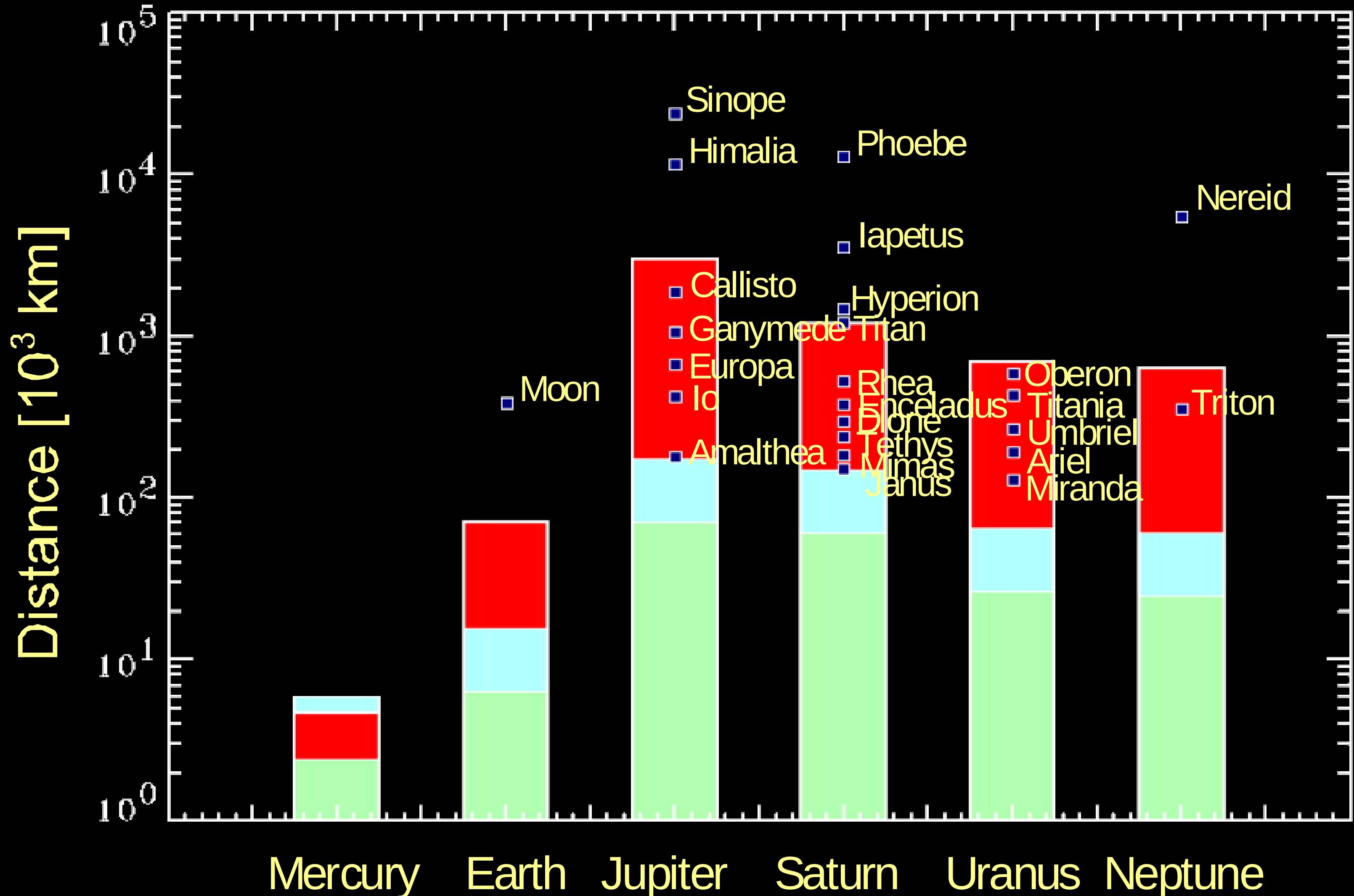




RDM = radiation design margin

Conclusions

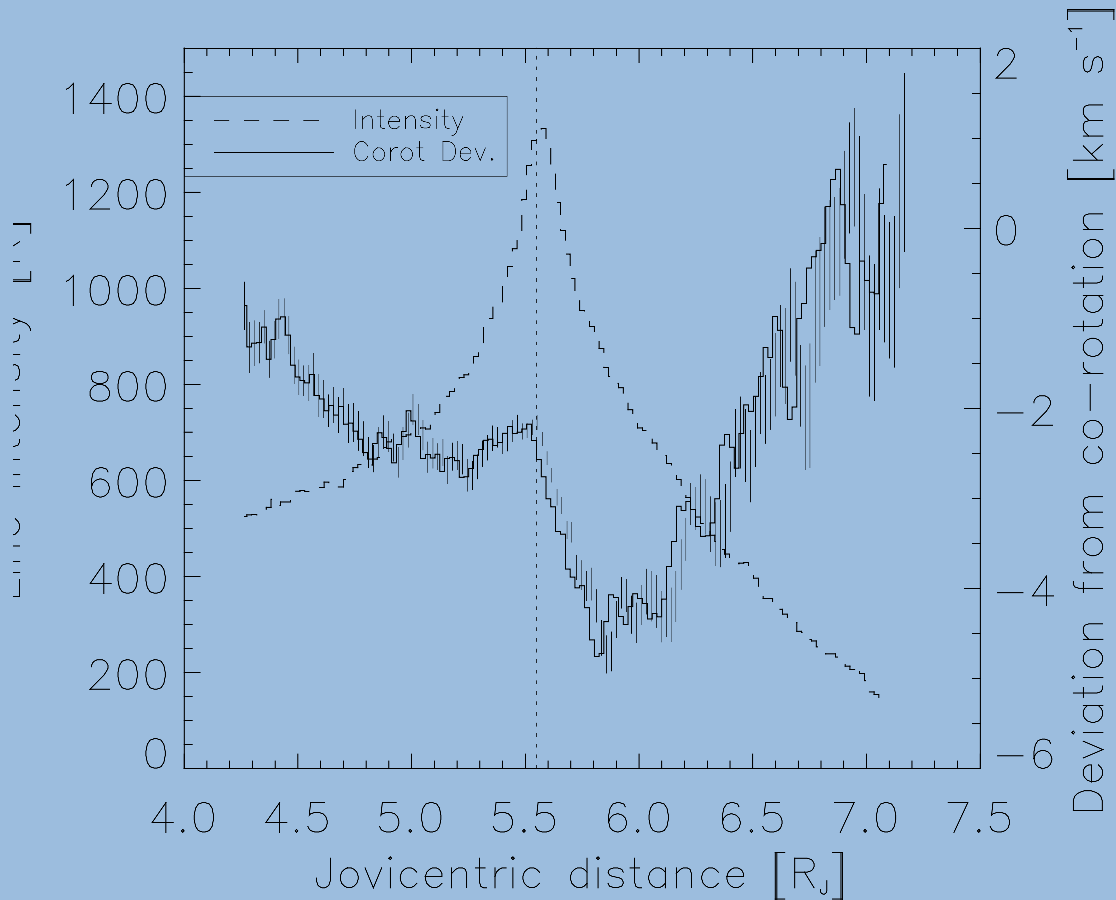
- Io's activity has erased any trace of surface evolution prior to ~2 10^7 years ago.
- That activity has "polluted" the surface of the other satellites.
- Absence of water (in any form) places constraints on the formation mechanism.
- Laplace resonance is probably old (>0.5 Gyr).
- Further progress can be made IF Io's composition can be investigated.
- Internal composition can be sampled by a "fly-through" mission which need not be vastly expensive.

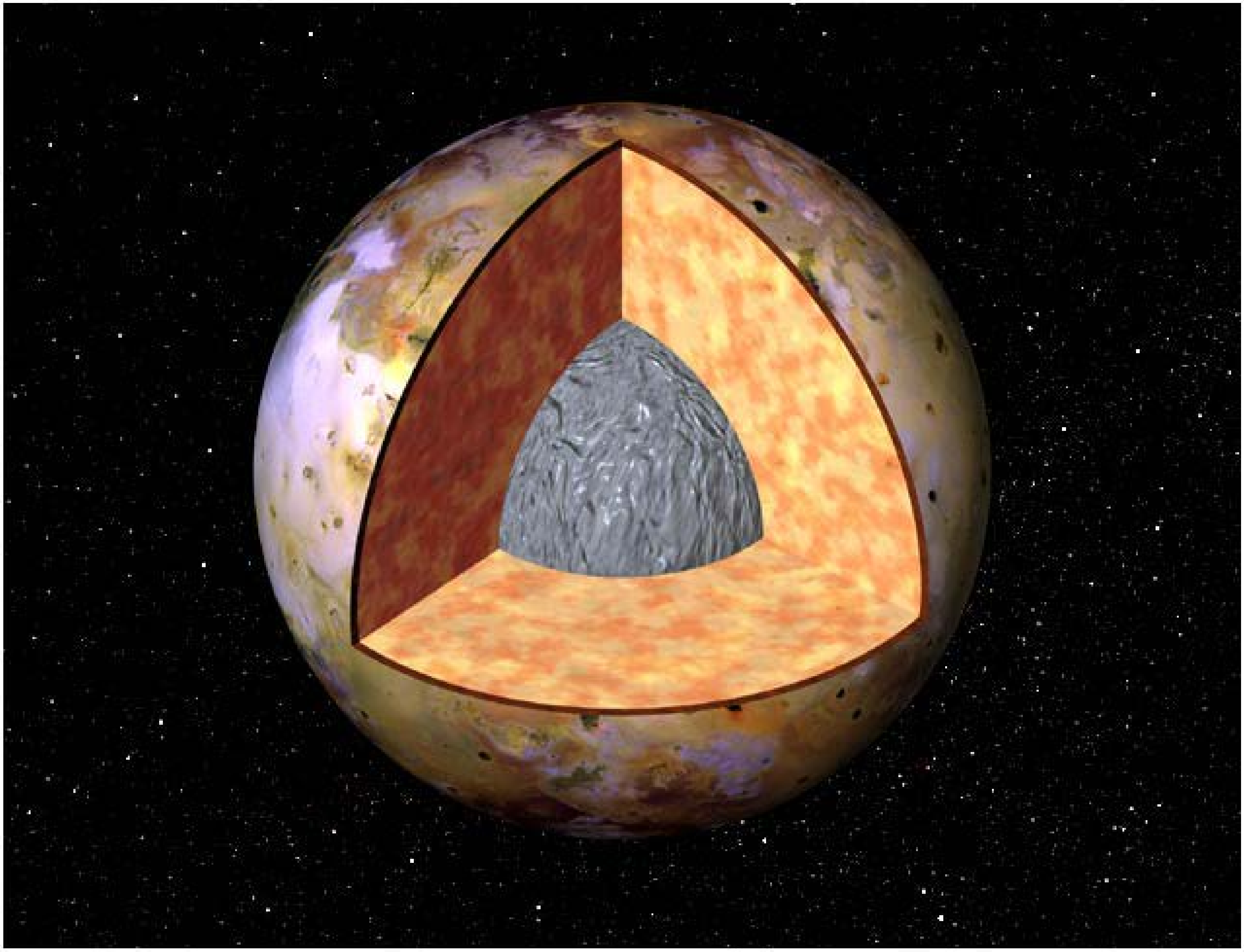


Plot concept “stolen” from Axel Korth

Deviation from co-rotation in Jupiter's magnetosphere (SIII)

b
UNIVERSITÄT
BERN





The Interior of Io

Satellite Formation Models

- Accretion disc
  - Circum-Jupiter disc as solar nebula gas flows in
- Spinout disc
  - Stranded material as Jupiter cools and contracts
- Blowout or impact-generated
    - Perturbation of Jupiter’s axis??
- Gas-free co-accretion disc
  - Small body collision with Jupiter’s Hill sphere
    - Composition gradient??

(see McKinnon, 2007)

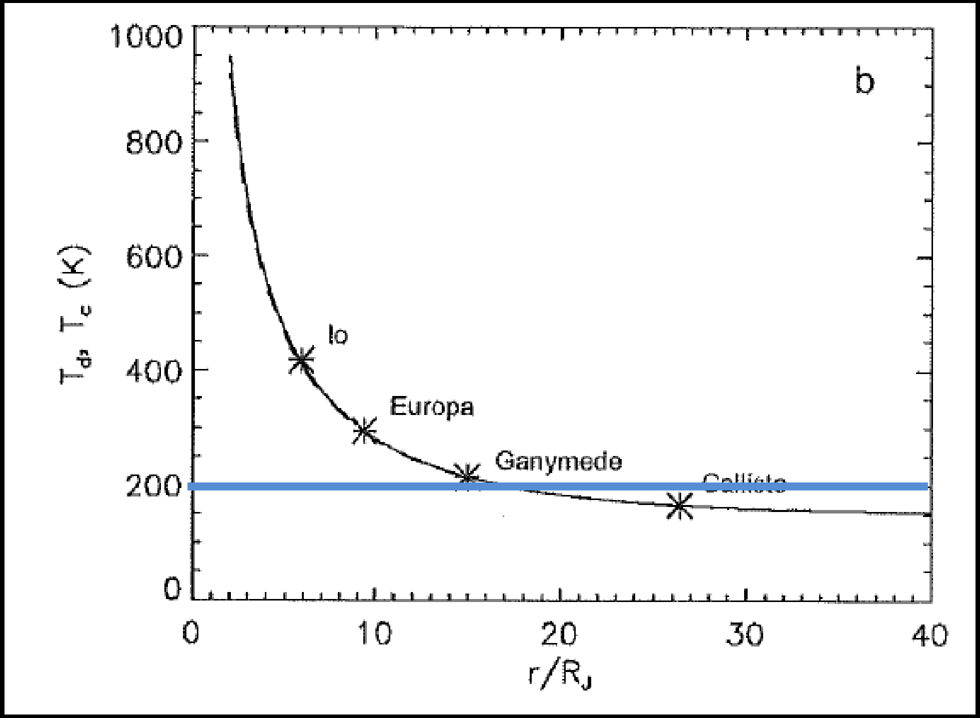
Formation?

- Following core accretion of Jupiter, the accretion of gas and dust continued but did not terminate “cleanly”.
- The Galilean satellites may have formed from a gas-starved, accretion disc.
- The satellite disc was probably fed until the solar nebula was no longer present to feed it.
- Given the ages of observed nebulae, Io probably formed within 10 Myr of solar system formation and possibly before solar hydrogen ignition.
- The temperature gradient (required to explain the depletion of water at Io but not at Europa) is strongly dependent upon many parameters which are poorly known.

(see McKinnon, 2007)

Energy Balance (Steady-State)

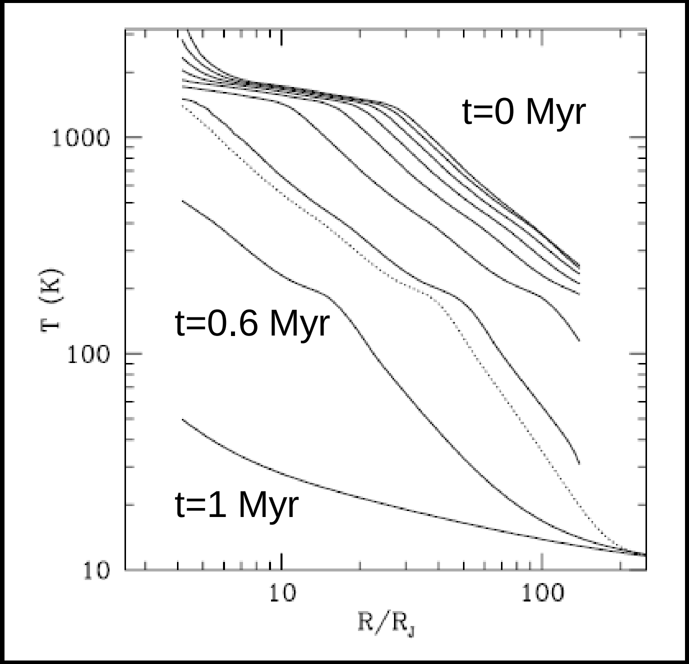
- Heat transfer
  - Jupiter's luminosity
  - Potential energy of infalling matter
  - Viscous dissipation within disc
  - Illumination from the proto-Sun/solar nebula
  - Radiative cooling



Cf. free sublimation temperature of $H_2O \approx 200$ K.

(see McKinnon, 2007 after Canup and Ward, 2002)

Temperature Distribution in a Time-Evolving Inflow



- Alibert et al. (2005)
- Implies migration inward over large distances.
- Time scale for propagation of snow line is extremely fast.
- May be at odds with the idea that post-formation Io should evolve outwards (acceleration by Jupiter).

Is the Laplace resonance stable?

- Lainey et al., Nature, 2009 claim that the system is evolving OUT of the Laplace resonance (at the 3 sigma level).
  - Io moves inwards, towards Jupiter, and loses more orbital energy by dissipation of solid-body tides raised by Jupiter and by the Laplace resonance interaction than it gains from the exchange of angular momentum with Jupiter's rotational energy through tidal dissipation in Jupiter.
  - This would be surprising since it would imply we are at a preferred time but ….