

The Future of Io Exploration

Report of the Io Community Panel for the Decadal Survey

Plus modifications for OPAG consumption...

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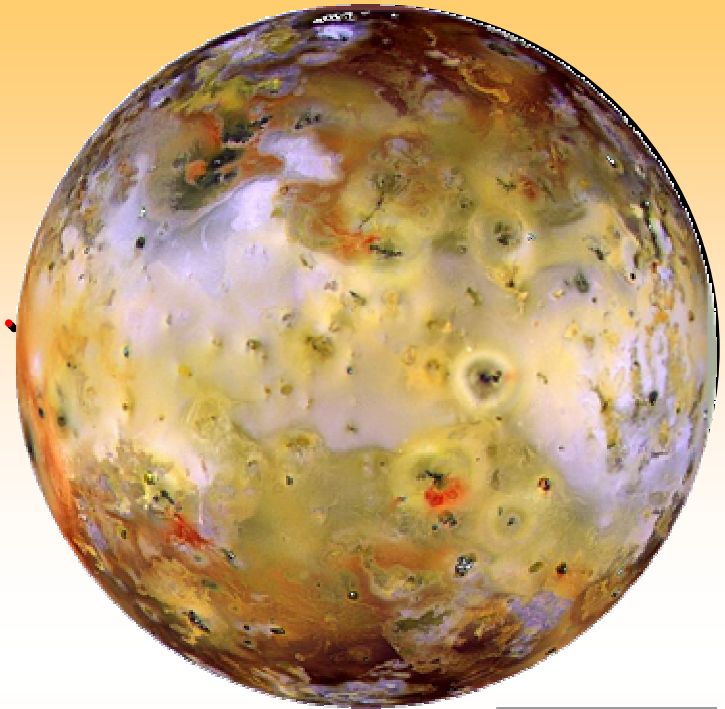
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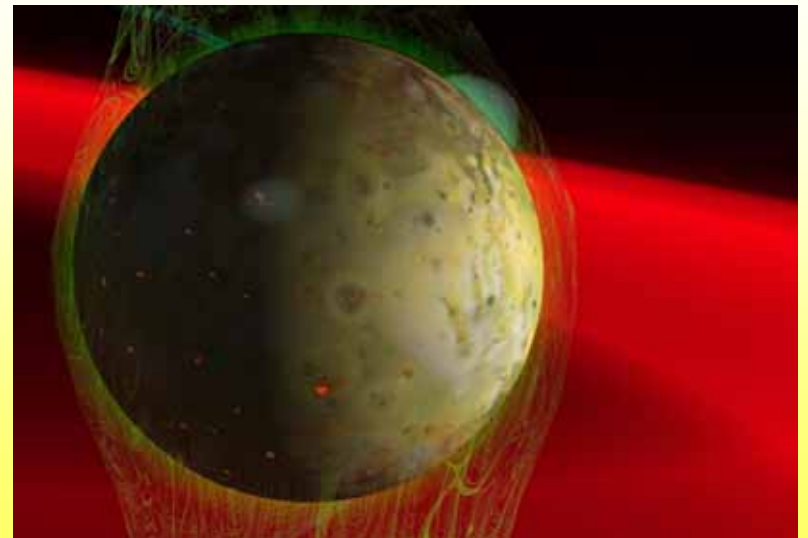


Io is the most dynamic body in the Solar System:

The only place beyond Earth where we can watch large-scale geology in action

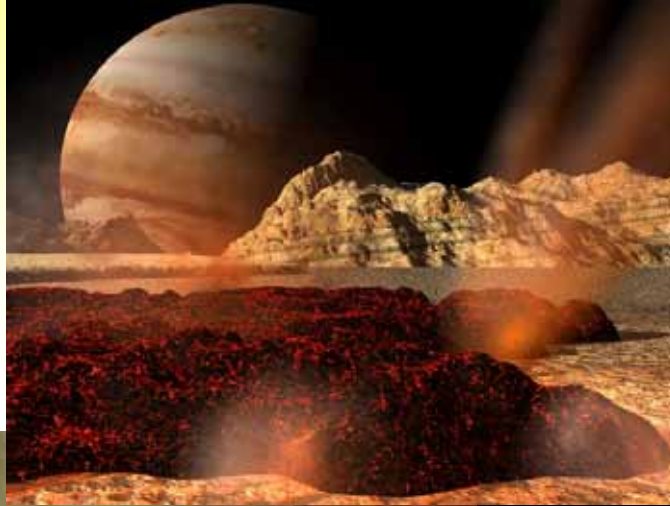
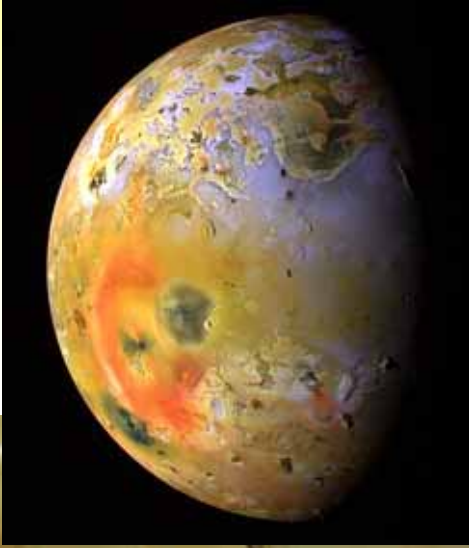


Extremely rich array of interconnected orbital, geophysical, geological, atmospheric, and plasma phenomena



Io's dynamism, contd.

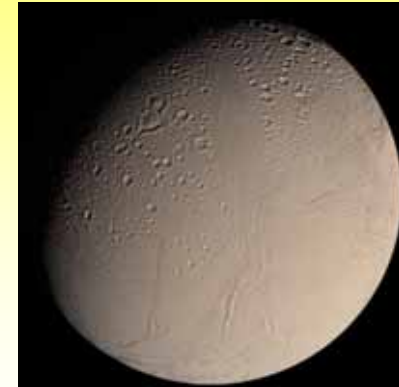
- One of the most spectacular places in the solar system: unique E/PO appeal



Tidal Heating, Magnetospheric Influence

Io is the best place to study tidal heating

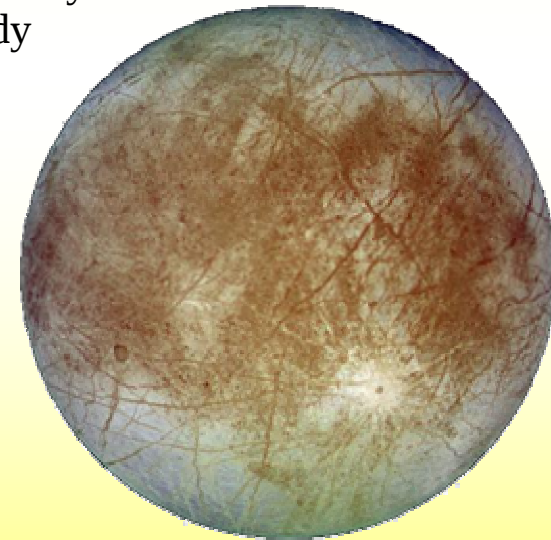
- Fundamental planetary process: important for the evolution of many planetary satellites
- Greatly expands the potential habitability zone for extraterrestrial life
- Extreme magnitude of tidal heating on Io makes it easy to study there- can be measured directly
- Tidal Insights into Europa:
 - Orbital eccentricities and tidal heating of Io and Europa are coupled by the Laplace resonance, but Io's tidal heating is much easier to study



Enceladus

Io's current tidal heating $\geq 2x$ equilibrium value ?

- o May result from oscillations in Io's Q and eccentricity
- o Oscillations would also involve Europa
- o Must be understood if we are to understand tidal heating of Europa, stability of its possible ocean



Io plays a fundamental role in the Jovian magnetosphere

- Iogenic plasma dominates the magnetosphere
- Magnetospheric sputtering and implantation by Io-derived material is a major modification process on the icy Galileans, especially Europa
 - Might be a source of chemical energy for European life

Io provides a unique insight into Earth history

Io's heat flow: 40x terrestrial

- Similar to terrestrial heat flow when life began? Illuminates the effects of high heat flow on:
 - Style, composition of volcanism
 - Volatile delivery to the surface
 - Volcanic burial of volatiles
 - Tectonic response to very high heat flow: no plate tectonics?
 - Crustal differentiation processes
- Despite differences in volatile inventory, the analogy already seems useful
 - Evidence for komatiitic volcanism on Io: only common on earth in the Precambrian
 - Earth's upper mantle now too cool for komatiite production

Provides analogs for large Phanerozoic eruptions

- Many terrestrial eruption styles have never been witnessed by humans
 - Flood basalts
 - Large explosive eruptions
- Such eruptions may have ~~global~~ consequences for the biosphere
- Also are a hazard to human civilization
- Io gives a chance to watch these processes in action!

Add Moon...



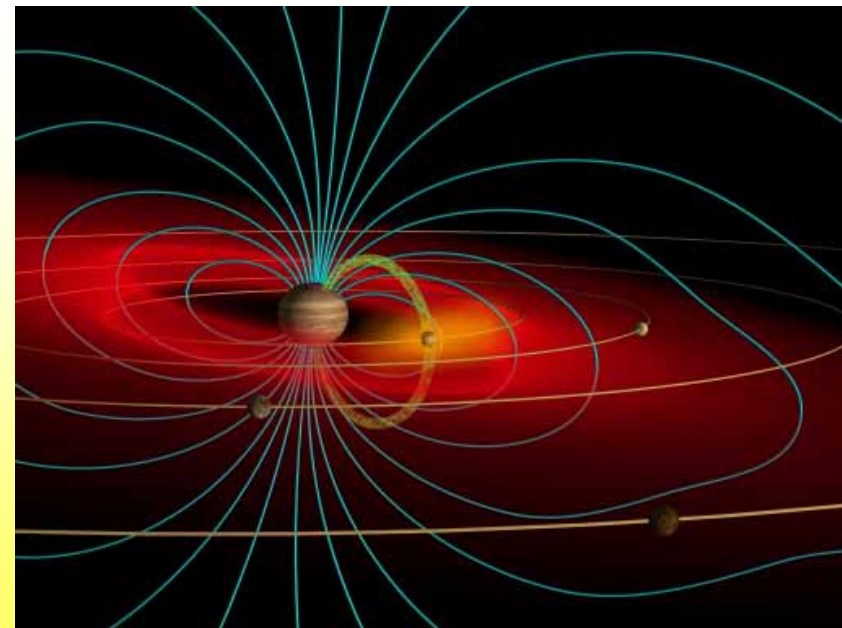
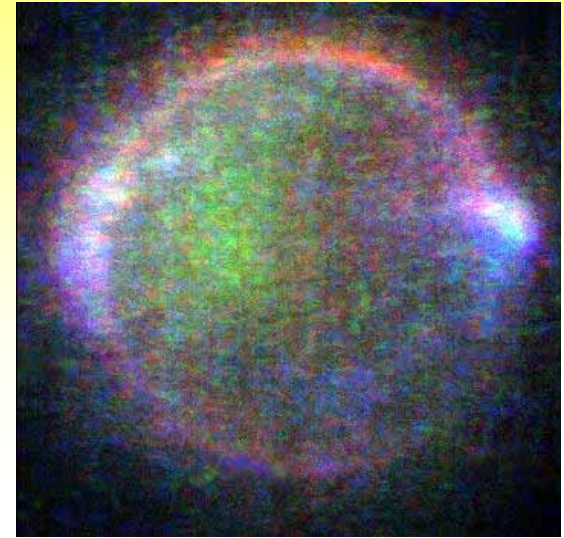
Io is a unique laboratory for atmospheric and plasma physics

Atmosphere:

- Unique P,T regime not accessible elsewhere
- Both volcanic and sublimation components
- Again, dynamism allows to watch processes in action and thus understand them
- Mass loss provides analogs for comets, early evolution of planetary atmospheres
- Studies are currently data-starved

Plasma:

- Extreme examples of common processes
 - Mass loading of plasma
 - Alfvén waves
 - Coupling of distinct plasma populations (torus, ionosphere)
 - Auroral activity
- Exoplanet magnetospheres may be observable
 - Distinctive emissions
 - Large emitting area



Unanswered questions: 1

Interior composition and structure

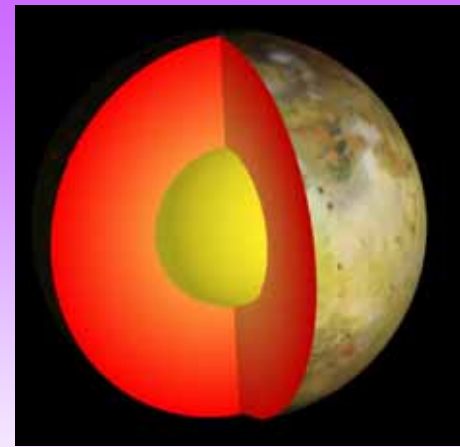
- Core size/composition?
- Why no magnetic field?
- Mantle composition
- Is there a differentiated crust, or is everything recycled?
- Was Io formed anhydrous, and if not, how did it lose its water?

Heat Flow

- Magnitude?
- Spatial variations across Io?
- If not in equilibrium, why not?
- How does it vary with time?
- Site of dissipation?

Surface Chemistry

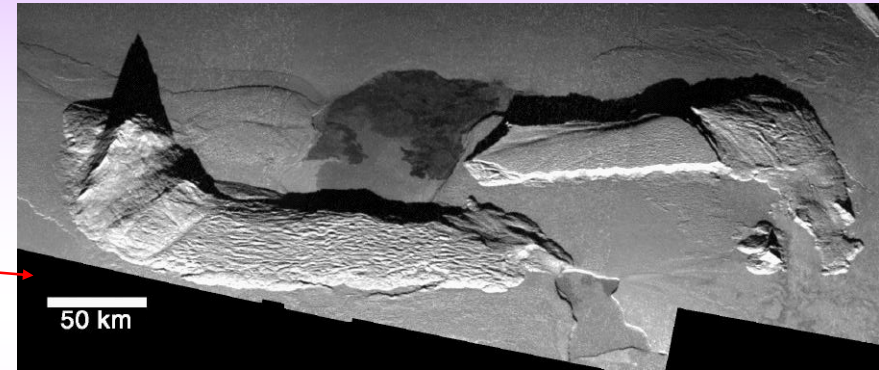
- What's there apart from S, O?
- Where does the sodium, chlorine come from?
- Why is the surface so colorful?
- Latitudinal compositional gradients: why no polar caps?



Unanswered questions: 2

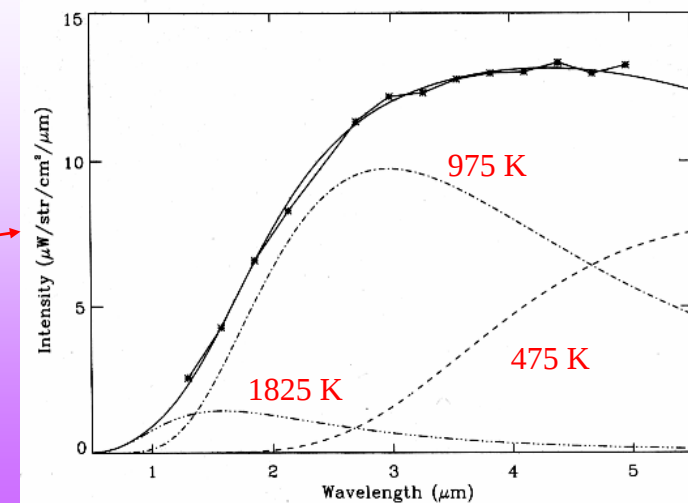
Tectonic and Surface Processes

- Erosion on an airless body
 - Origin of “sapping” features?
 - Gullies, “dunes”?
- Tectonism:
 - Crustal thickness?
 - Why no plate tectonics?
 - Origin of mountains: crustal compression due to resurfacing?
 - Are some calderas tectonic?



Volcanism

- How do very large volcanos behave?
 - Can test volcano models under extreme conditions
 - Applicable to large-scale volcanism on Earth, Venus, Moon, etc.
- What's the magma composition, and its range?
- If not ultramafic, why are the magmas so hot?
- Do silicic or sulfur flows exist?
- Plume generation mechanisms:
 - Why are some plumes so long-lived?
 - What's the mass and composition of the plume dust?



Unanswered questions: 3

Surface age, cratering timescales

- How old is the surface, on average?
 - Galileo evidence shows much resurfacing is localised
- Relative importance of effusive, pyroclastic, resurfacing
- Are there any impact craters on Io?
 - If so, can we use them to calibrate cratering timescales in the Jovian system?

Atmosphere

- The “missing link” between the surface and magnetosphere: not well understood due to observational difficulties
- Importance, magnitude, variability of volcanic source?
- Importance of sublimation: diurnal variations?
- What happens to the SO_2 that should freeze out at high latitudes?
- Chemistry: what's there apart from SO_2 , SO , S_2 ? How do species interact?
- Heating/expansion of upper atmosphere by plasma?
- How are the various UV, visible, emissions excited?
- Is the ionosphere global? How is it maintained?

Unanswered questions: 4

Mass loss, plasma interaction

- Loss mechanisms
 - Direct ionization by impacting plasma?
 - Stripping of an ionosphere?
 - Io-local vs. extended source of plasma?
- How are Na, Cl, lost?
- What stabilizes the plasma source?
- Role of plumes
 - Direct plume/magnetosphere interaction?
 - Supply of dust to the magnetosphere?

Magnetosphere

- Energy path between Jupiter's rotation and the terawatts of EUV emission?
 - Ionization?
 - Charge exchange?
 - Wave/particle interactions?
 - Global electric fields?
- Radial transport of the plasma?

Galileo's Limitations

- 1980-vintage instrumentation
 - Small, radiation-sensitive CCD, no UV imaging
 - Limited UV spectroscopy (very low spatial, spectral, resolution)
 - 17-element InSb array, no hi-res Io spectra due to grating problems
 - Primitive (single-aperture) mid-IR instrument
- Very low data rate (~ 0.08 kbps)
- Result: very limited spatial, temporal coverage
 - Does not allow exploitation of Io's unique time-variability

Things we will never know about the volcanos from Galileo Data

- Full range of eruption styles (*insufficient spatial, temporal coverage*)
- Lava composition (*no spectra of fresh lava, only lower limits to magma temperatures*)
- Eruption volumes (*flow thicknesses not well constrained*)
- Time evolution of the magma output (*insufficient time coverage, inadequate mid-IR capability for mapping old warm flows*)
- Gas and pyroclastic composition of plume eruptions, and its time evolution. (*inadequate UV instrumentation, insufficient time coverage*)
- Eruption effects on the atmosphere (*inadequate UV instrumentation, insufficient time coverage*)
- Eruption effects on the torus (*insufficient time coverage*)

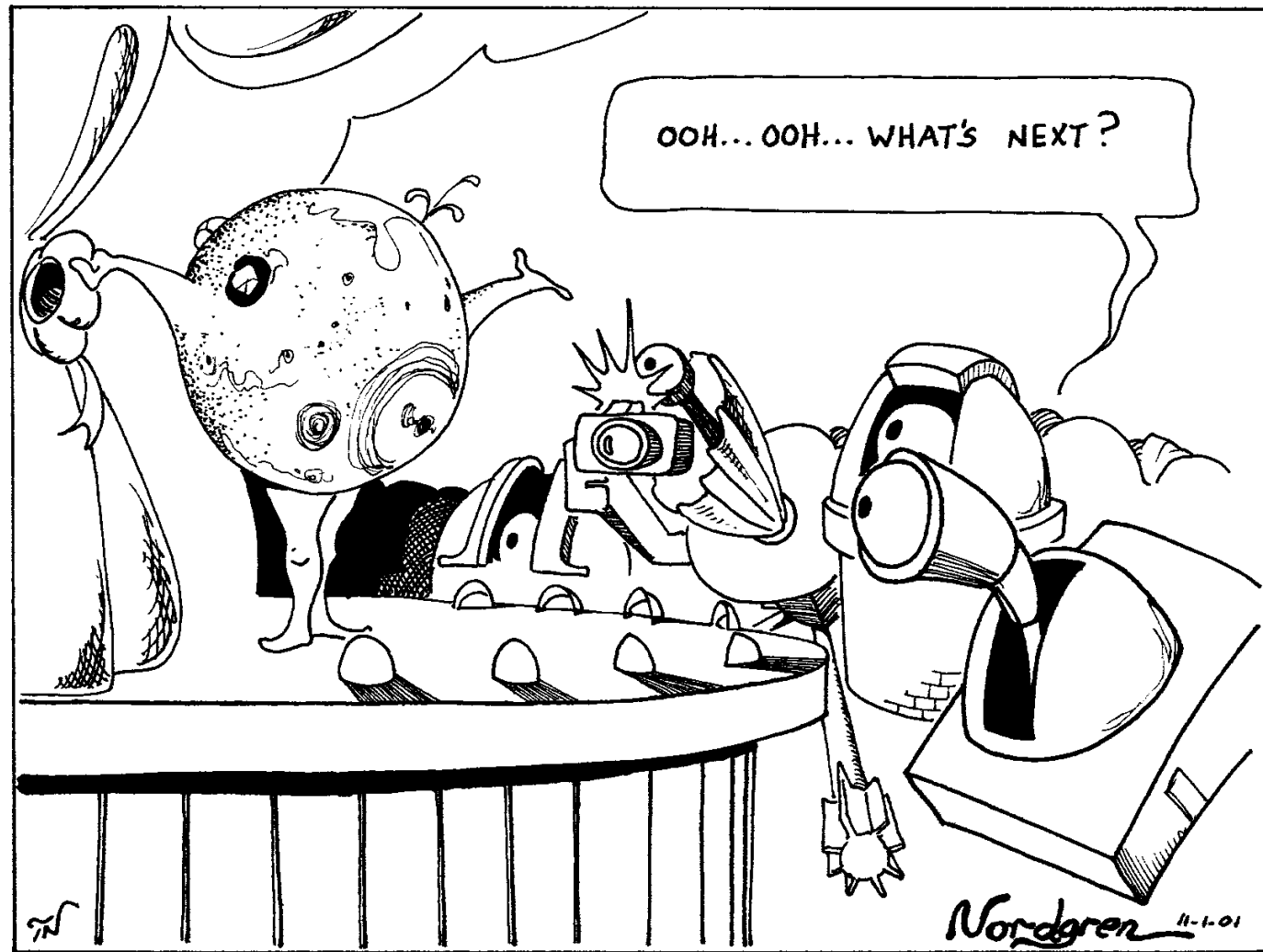
Insufficient data to fully understand the eruption, draw analogies with the Earth

The Future: The Need for Long-Term Monitoring

Cartoon by Tyler Nordgren
Tyler_Nordgren@redlands.edu

We learn a lot about Io by simply watching it until it does something spectacular

No “snapshot” shows the full range of important phenomena



Future Spacecraft Exploration

Io Orbiter?

- Proposed in previous roadmaps, probably not realistic in the next decade, given EO experience (radiation, delta-V)

Flyby Mission ?

- Doesn't investigate, exploit, Io's unique time variability

Jovicentric Orbiter: Most realistic, useful

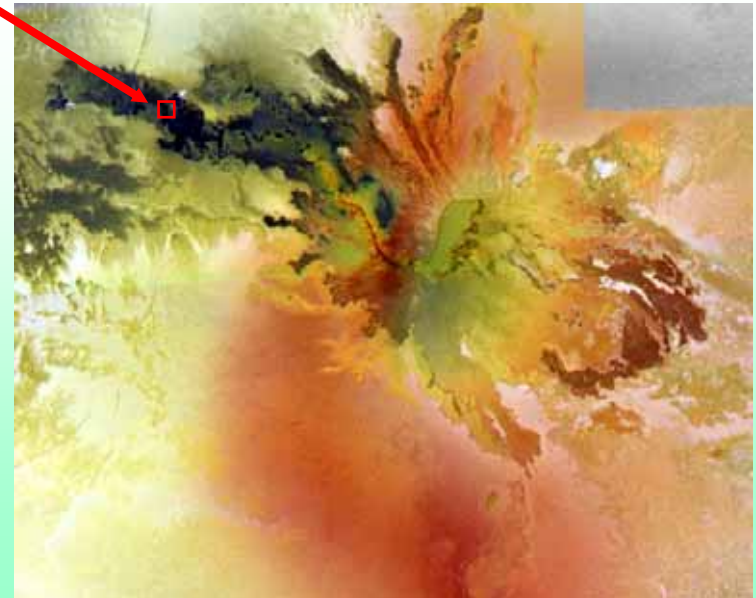
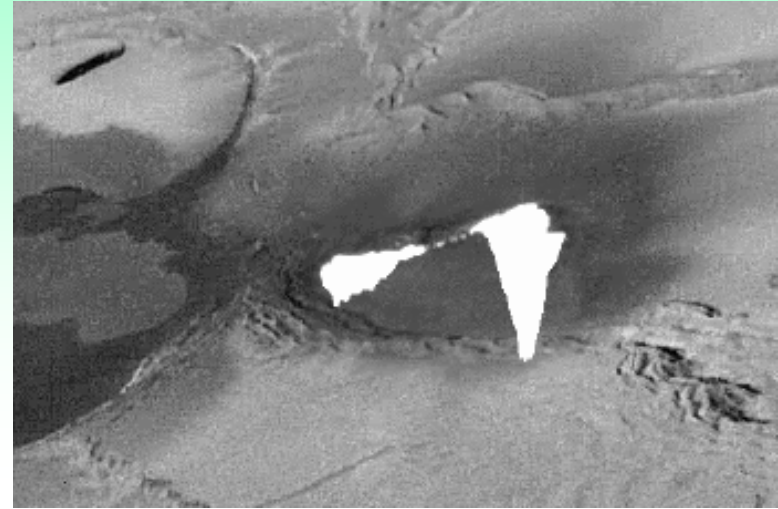
- Readily combined with magnetospheric and Jupiter studies ("Jupiter Polar Orbiter") or studies of the other Galileans: "Tidal Heating Explorer"
- Despite similar orbit and targets, could make great strides beyond Galileo for less cost
- Multiple flybys of same hemisphere, 1 month(?) spacing.

Watch evolution of individual volcanic centers

- Galileo has survived 7 Io flybys: radiation dose ~ 40 krad each
- Half EO hardness (2 Mrad) allows 50 Io flybys
- Use remainder of orbit for playback, distant monitoring
 - Data return per Io flyby @ 12 Kb/s: 10 – 30 Gbits (Galileo ~ 0.2 Gbits!)
 - Scan platform or simple mirror would allow monitoring during downlink
- 2 penetrators to determine composition, interior structure?

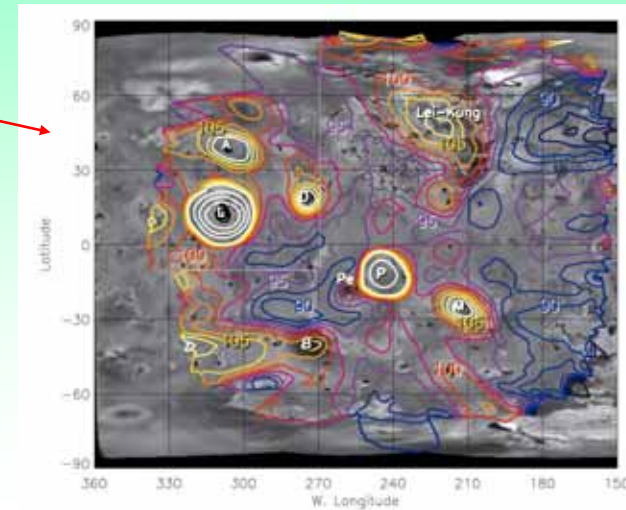
Io Mission Measurement Requirements:

- *Repeated* < 100 m resolution multicolor imaging of wide areas
- Smaller coverage at higher resolution
- Topographic mapping (laser or stereo), 2 m relative precision
- 0.5 – 5 micron spectroscopy with < 1 km spatial resolution. Provides:
 - Compositional constraints on fresh lavas
 - Temperature information- constrains composition and eruption style



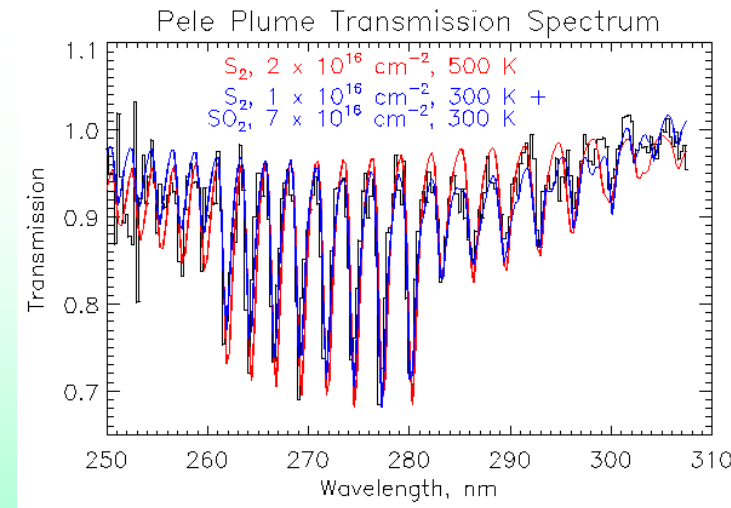
Io Mission Measurement Requirements: contd.

- 10, 20 micron thermal mapping, 10 km resolution
 - Measures heat flow, total lava output
- 0.20 – 0.32 micron UV spectroscopy, 20 km resolution, for detailed spatial mapping of atmosphere and plumes
 - Solar occultation capability for high S/N



Geophysical measurements:

- Tidal flexing amplitude constrains asthenospheric viscosity, dissipation mechanisms
 - Passive optical techniques?
 - Laser altimetry?
 - Difficult from Jovicentric orbit, but perhaps possible, given multiple flybys with similar geometry
 - Penetrator?
- Gravity during close passes for internal structure, crustal density (via topography/gravity correlations)



Io Mission Measurement Requirements, contd.

- Plasma instruments capable of mapping 3-D velocity distributions of electrons and individual ion species
 - Need ability to separate O^+ from S^{++} , so not just M/Q
- Neutral mass spectrometer for close flybys?
- Penetrators:
 - Retro-rockets needed- non-trivial.
 - Short lifetime may be OK: Io probably extremely seismic
 - Seismometers for internal structure measurements using probable abundant natural seismicity
 - o Need two simultaneous stations
 - o Determine tidal flexing from low-frequency seismometers
 - Atmospheric mass-spec for compositional measurements on entry
 - In-situ surface composition?
 - o alpha proton x-ray spectrometer?
 - o mini-thermal emission spectrometer?,
 - o gamma-ray spectrometer?

Space-Based Telescopes

Ultraviolet capability is key

- SO_2 , S_2 , SO absorptions 2000 - 3000 Å
- Atomic emissions 1000 – 2000 Å
- Ly-alpha absorption imaging of atmosphere

BUT no advances in space-based UV telescopes are currently planned.

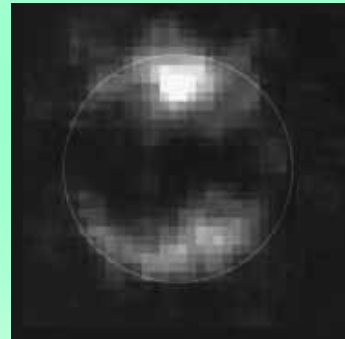
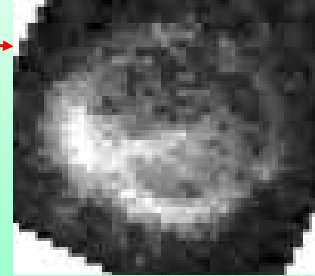
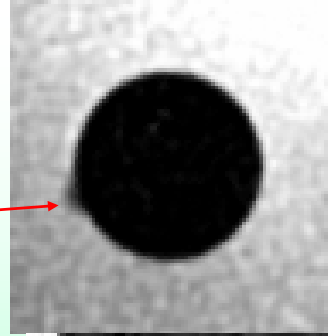
- HST UV instruments have limited sensitivity
 - Mapping Io's atmosphere is very difficult due to low S/N
- HST due for retirement in 2010
- NGST has no UV capability

Much could be accomplished with improved-sensitivity detectors, diffraction-limited UV imaging

There is a clear need for a UV-optimized successor to HST, dedicated to or at least optimized for solar system work

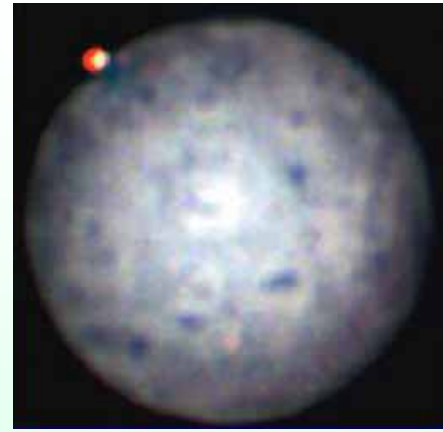
A dedicated Io/Jupiter UV telescope could provide synoptic monitoring

- Necessary to understand the time variability that reveals physical mechanisms, in the atmosphere and torus
- A general-purpose UV telescope could not provide sufficient monitoring time

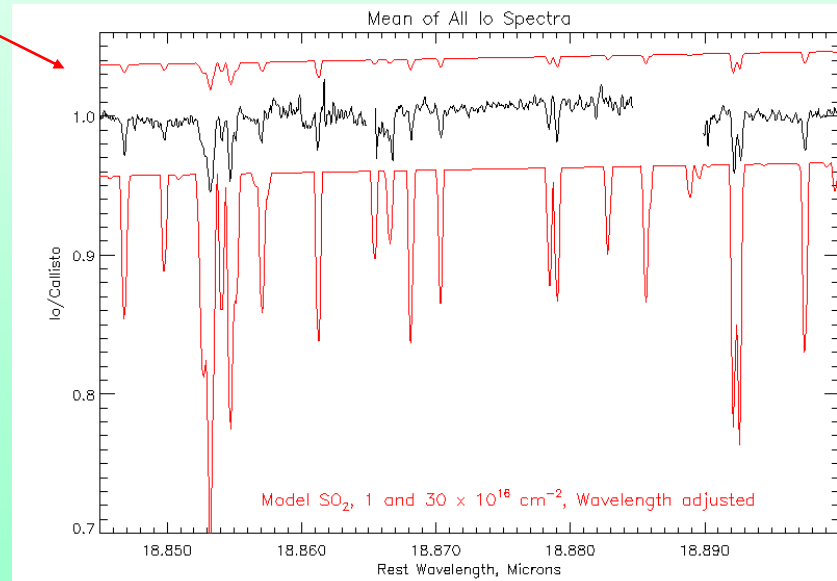


The Future of Groundbased Observations

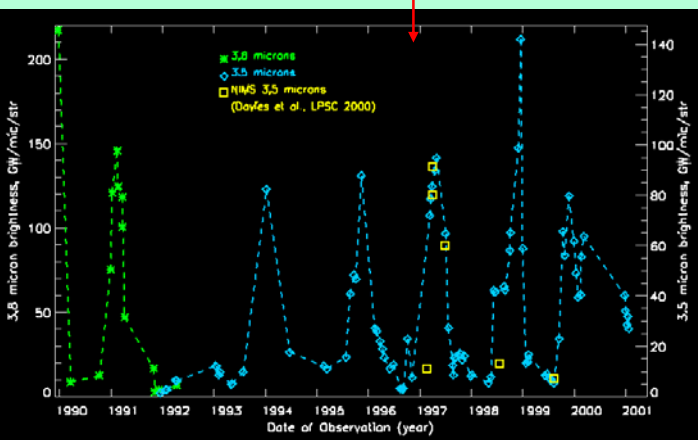
- Need telescopes that can conduct long-term, multi-wavelength, monitoring
 - Queue scheduling can help if well implemented: frequent brief observations are key
 - Dedicated facilities would be even better
 - Future Io missions should have ground-based support facilities in their budgets
- 8-10 m telescopes, AO, allow detailed disk-resolved studies of Io.
 - Routine mapping of Io's atmosphere in mid-IR
 - Mapping of heat flow distribution?
 - Hot spot distribution, temperatures, evolution
- Small telescopes are also important
 - Better temporal, poorer spatial resolution



Tvashtar eruption from Keck



Io's SO₂ atmosphere at 18.9 microns, IRTF/TEXES, Spencer, Richter, Lellouch, et al. Nov. 2001



Loki time history, IRTF

Conclusions

- Io is one of the most exciting targets for future solar system exploration, with much to teach us about fundamental problems in planetary science and the Jupiter system in particular
- Io is the only place beyond Earth where we can watch geology as it happens
- Phenomena occur unpredictably and are seen over a huge range of wavelengths: need synoptic monitoring using multiple techniques simultaneously
- The next Io mission should be a Jovicentric orbiter, perhaps with penetrators
 - High inclination orbit: could be part of a Jupiter Polar Orbiter with magnetospheric, auroral exploration as an additional goal
 - Low inclination orbit: could be part of a mission to all the Galilean satellites: “Tidal Heating Explorer”
- A UV- and planetary-optimized space telescope is needed to replace and extend HST’s capabilities
 - In addition, a Jupiter/Io dedicated telescope could provide crucial temporal coverage
- Ground-based facilities provide essential support for missions, with better temporal coverage for a fraction of the cost
 - Groundbased support should be part of future missions
 - Large telescopes with AO provide HST-like spatial resolution in the near-IR: NASA should make more time available on such facilities
 - Small telescopes provide the best temporal coverage and should also be supported