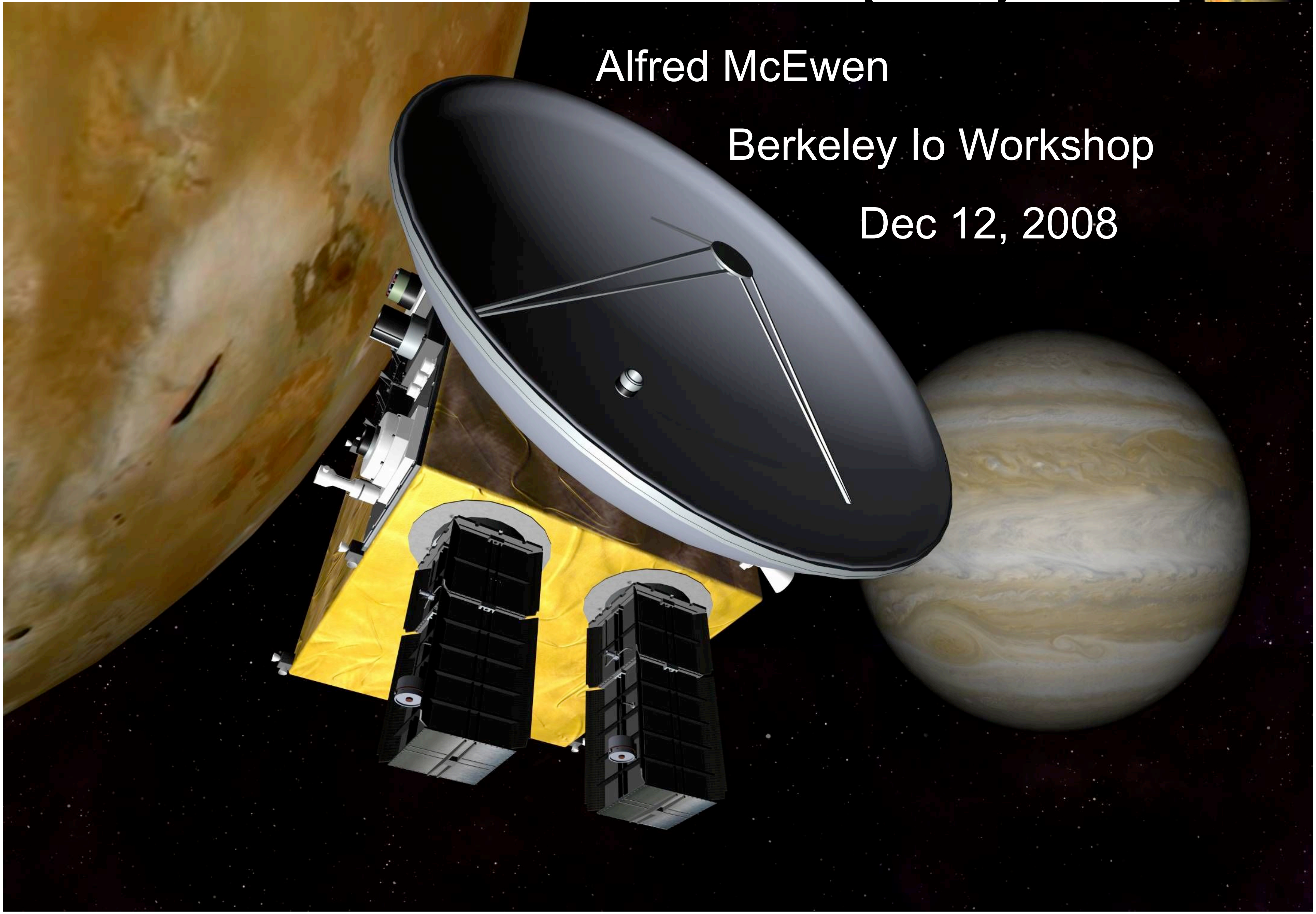
Io Volcano Observer (IVO)



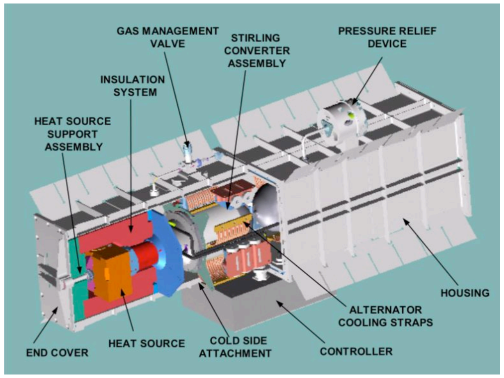
Alfred McEwen

Berkeley Io Workshop

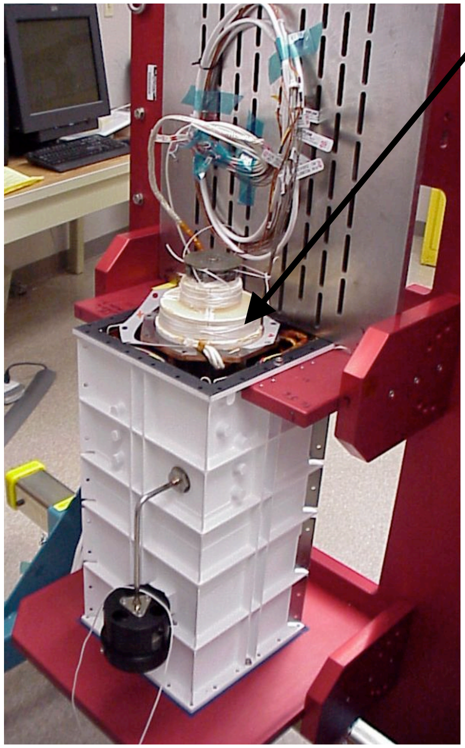
Dec 12, 2008

Advanced Stirling Radioisotope Generator (ASRG) Engineering Unit

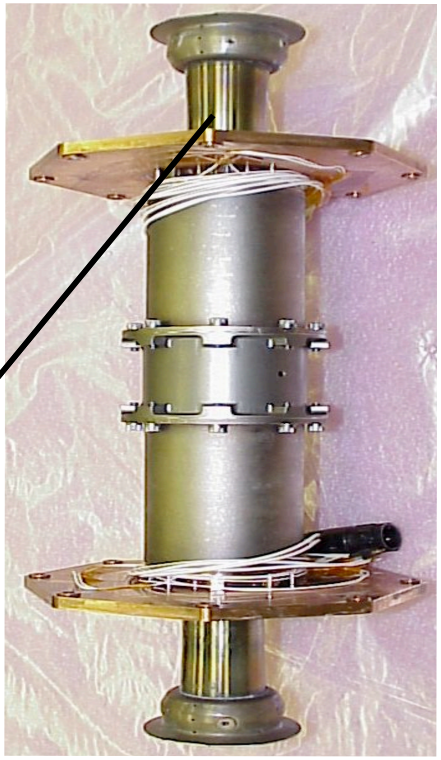
- Operation in space and on surface of atmosphere-bearing planets and moons
- Characteristics:
  - ≥14 year lifetime
  - Nominal power : 140 We
  - Mass ~ 20 kg
  - System efficiency: ~ 30 %
  - 2 GPHS (“Pu^{238} Bricks”) modules
  - Uses 0.8 kg Pu^{238}
- Final wiring and connections for ASRG engineering unit underway
- Reliability to be demonstrated by the end of 2009
- NASA eager for Discovery-class test flight of ASRGs, hence 9 studies funded.



Lockheed Martin/Sunpower



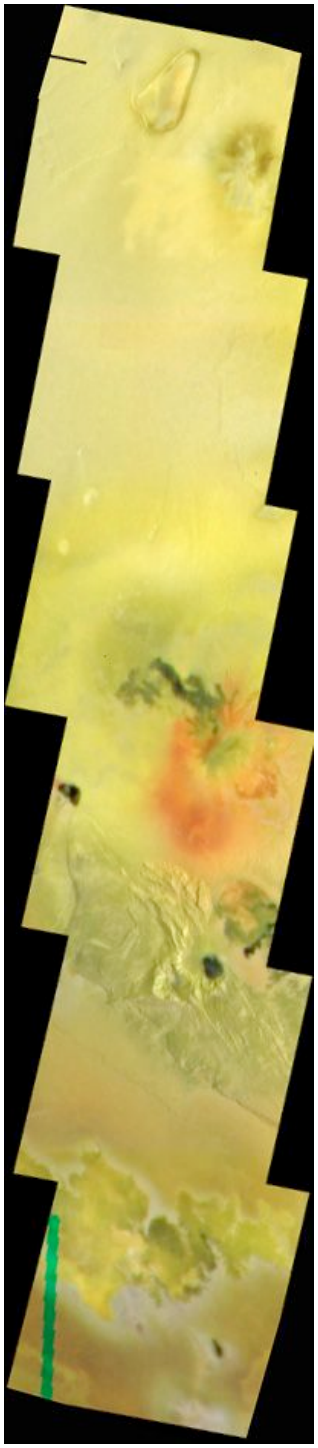
Outboard Housing and Paired ASC-Es



Paired converters with interconnect sleeve assembly

IVO Study Team

- ***PI/Science team***
  - *Alfred McEwen, UA, PI*
  - *Laszlo Keszthelyi (USGS), John Spencer (SwRI), Nick Thomas (U Bern), Torrence Johnson (JPL), Phil Christensen (ASU)*
- ***Instrument teams***
  - *US-built, mission floor:*
    - *Imaging: UA lead: McEwen, Chris Shinohara, others*
    - *Thermal mapper: ASU lead: Christensen*
  - *Contributed:*
    - *NMS: U. Bern leads: Nick Thomas, Peter Wurz*
    - *Magnetometer: IGEP lead: Karl-Heinz Glassmeier*
- ***Spacecraft team***
  - *Tim Girard (MSI), Gred Heinsohn (MSI), Shinohara (UA), Roberto Furfaro (UA), Thomas Gardner (RMS), Dan Cheeseman (RMS)*
- ***JPL team***
  - *Richard Beatty, Jan Ludwinski, Theresa Kowalkowski, Chen-wan Yen, Robin Evans, Insoo Jun, many others from Team X*

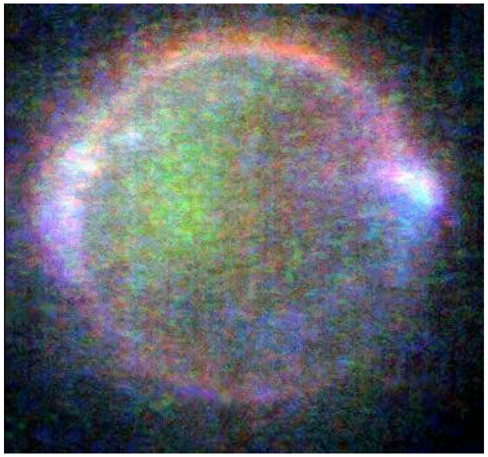


An Io Mission is High Priority to NASA

- Mentioned in planetary Decadal Survey for a New Frontiers Class mission
  - Also of great interest to Space Physics community
    - “Io is the heartbeat of the Jovian magnetosphere” - L. Frank
- An Io mission is on the list for NF-3, but not radioisotope power
  - A high data rate is needed given Io’s tremendous variability in geography, wavelength, and time. Large enough solar arrays pose many engineering challenges.
    - IVO will return >1000 times more data about Io than did Galileo
- Io is the most dynamic solid body in the Solar System!
  - The only place beyond Earth where we can watch large-scale geology in action
  - Rich array of interconnected orbital, geophysical, geological, atmospheric, and plasma phenomena
  - Unique E/PO appeal
  - Best place to study tidal heating, which greatly expands habitability zones of planetary systems
    - Io’s coupled orbital-tidal evolution is key to understanding tidal heating of Europa and stability of its subsurface water.
  - Provides unique insight into early volcanic processes on terrestrial planets

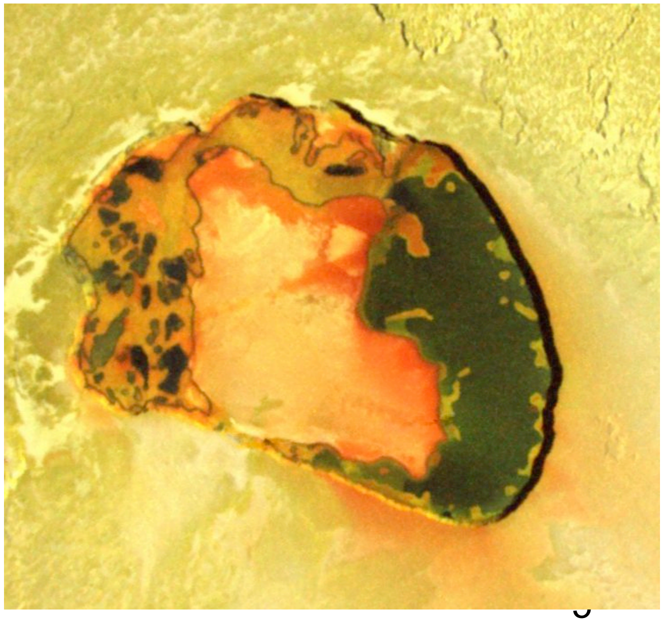
IVO Overview

- Our #1 goal for this study is to define a mission that fits Discovery
  - Really Discovery+ with government-furnished ASRG and NEPA
  - Stick to minimum acceptable science
  - Very simple spacecraft
- **Primary Science Objectives**
  - **1. Understand active volcanic processes on Io**
  - **2. Understand tidal heating of Io**
  - **3. Understand loss of material from Io and effects on the magnetosphere, plasma torus, and neutral clouds**
- **Technology Objectives**
  - **Test ASRG long-term and in intense radiation environment**
    - **Test microphonics via NAC**
    - **Make sure life test can continue if 1 ASRG fails**
  - **Information on Jupiter radiation environment for future exploration**



GLL image of Io in eclipse

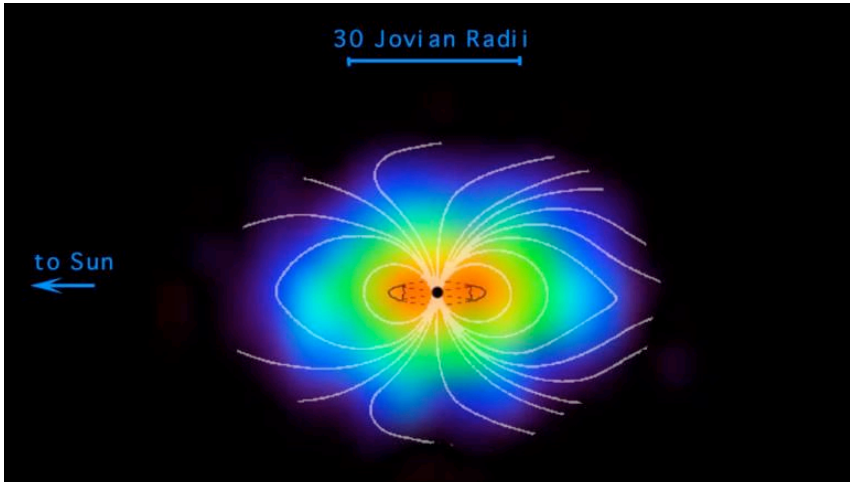
NH image of Io and Tvashtar plume



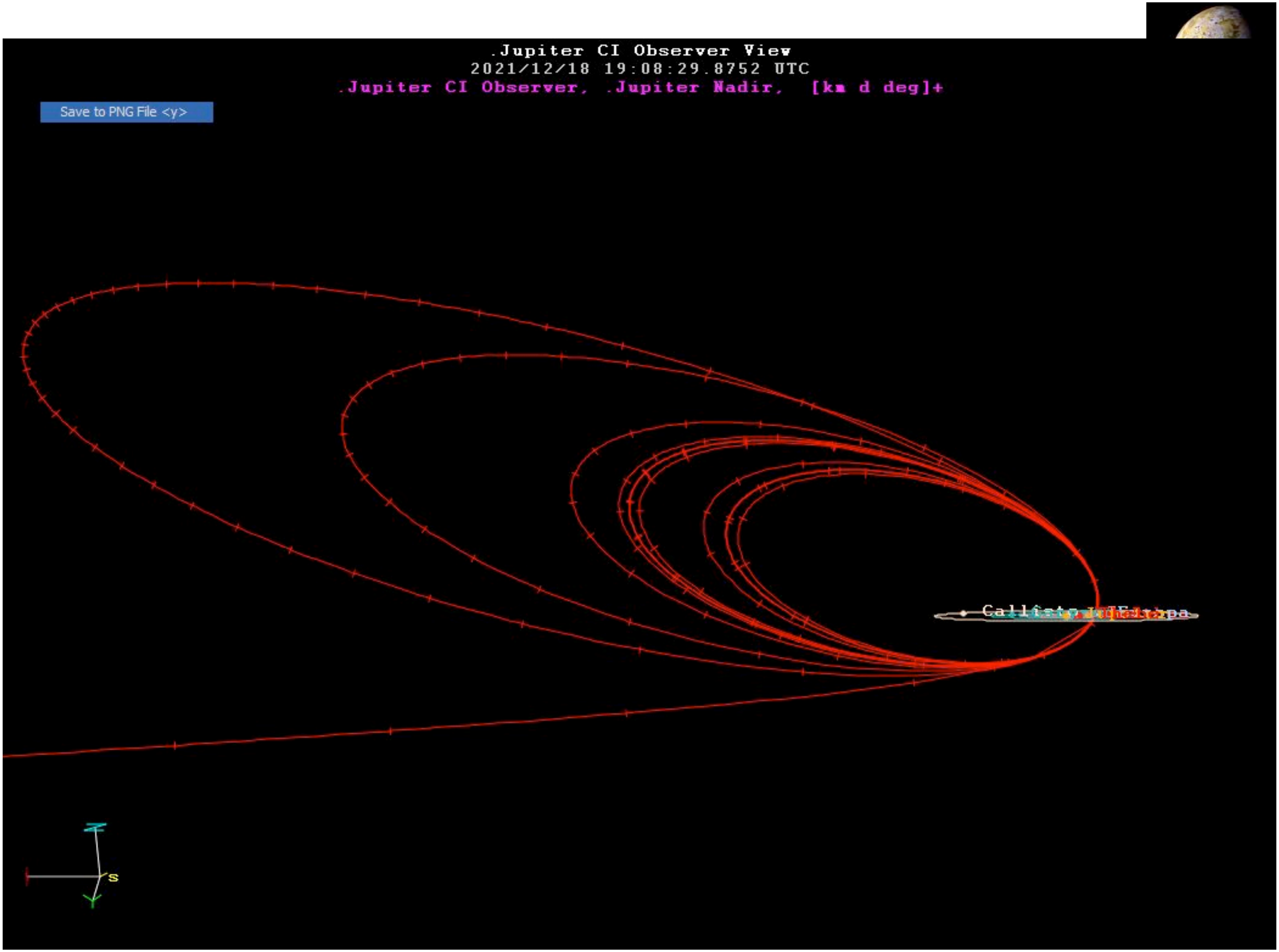
Tupan Patera

Trajectory Overview

- Plan for a trajectory to Jupiter launching in 2014-15 and a back-up in 2016
  - VEEGA trajectory in Jan 2015 looks best
- Io flyby before Jupiter Orbit Insertion (JOI)
  - Does not reduce delta-v for JOI, but unique science
    - Good equatorial view during approach
  - Will also get Jupiter system science on approach and after JOI
- Science orbit
  - High inclination (>45°) to Jupiter to lessen radiation exposure
  - Multiple close (100-1000 km) Io flybys



Charged particles around Jupiter (Cassini Ion and neutral camera)



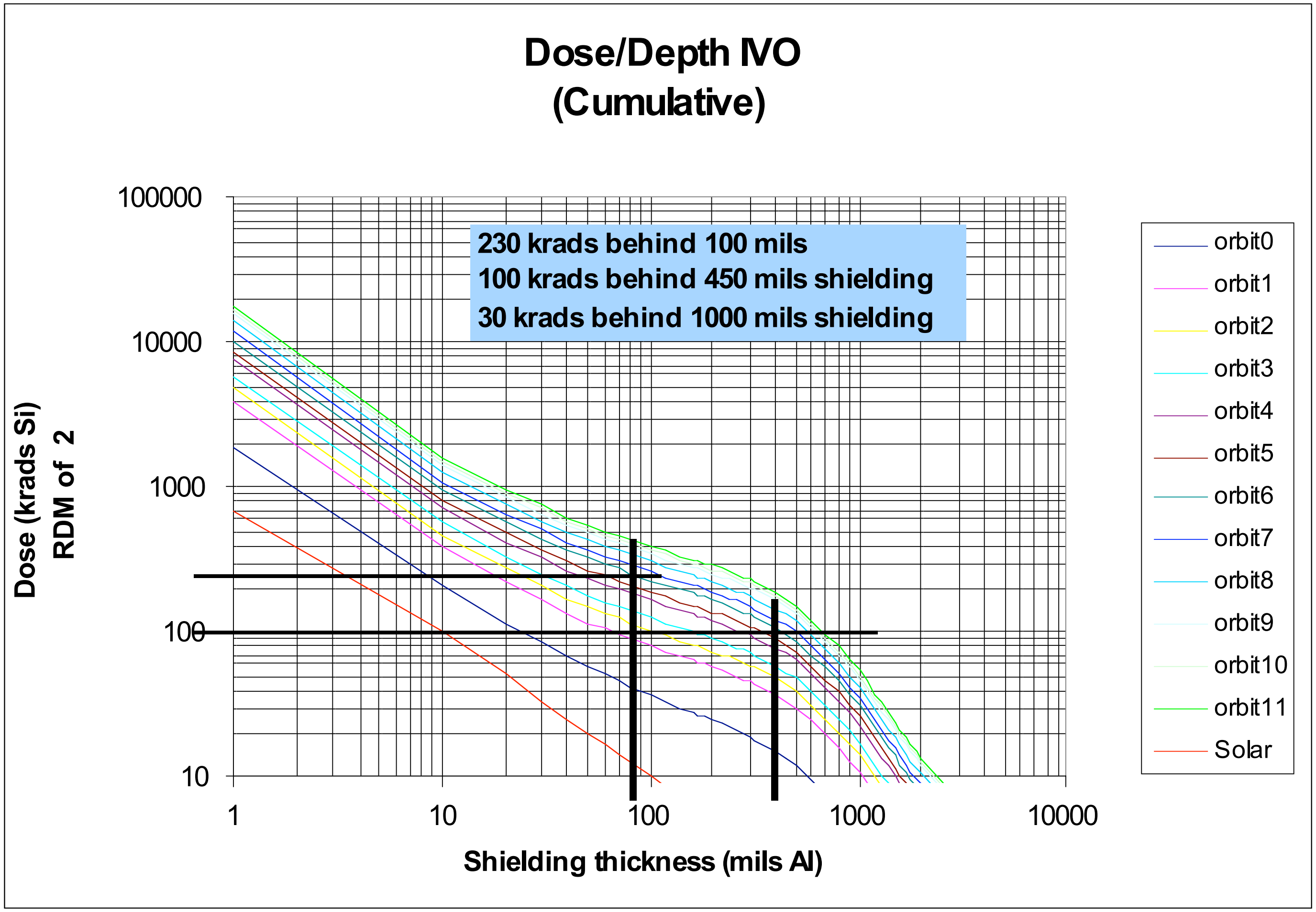
.Jupiter CI Observer View

2021/12/18 19:08:29.8752 UTC

.Jupiter CI Observer, .Jupiter Nadir, [km d deg]+

IVO Total Dose Environment

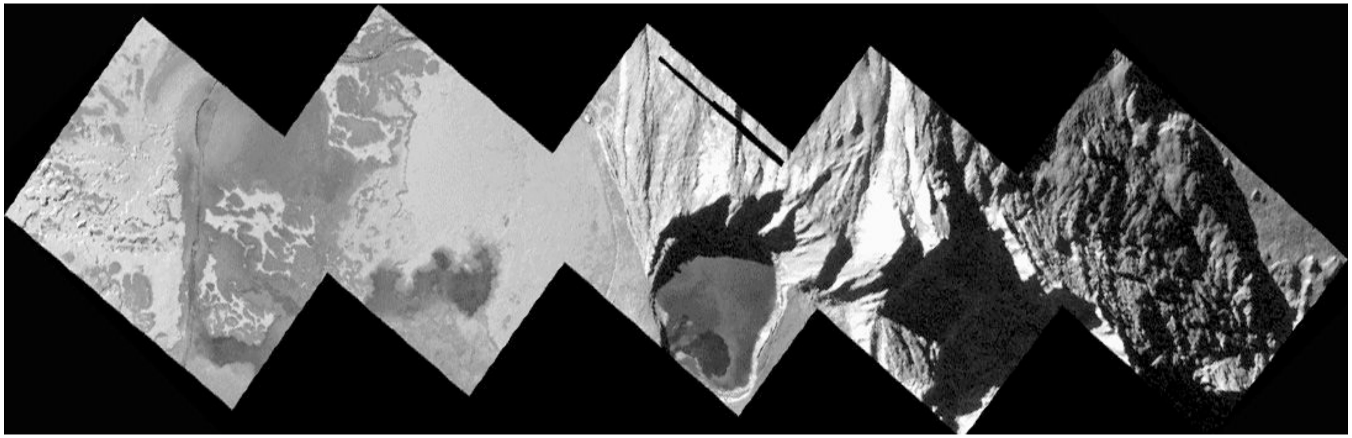
- Primary science achieved in 6 fast (~19 km/s) fly-bys
  - Expect 115 krads behind 100 mils, 230 krads with design margin = 2
  - Significant “free” shielding available from S/C elements reduces this to under 100 krads (RDM 2) for electronic parts
- Radiation “vault” and spot shielding planned
  - 200 kg shielding mass planned



Orbital Phase

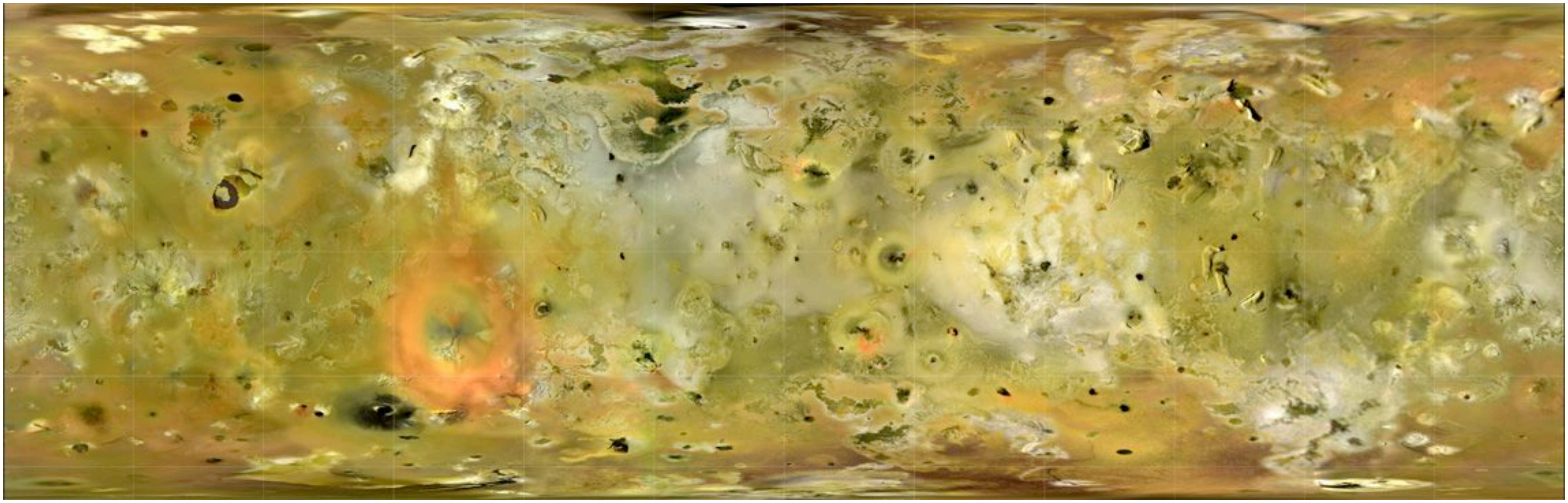
- Current plan is to insert into a long period orbit (~200 days) to keep JOI delta-V low
- Io flybys used to “pump down” the period to ~30 day orbit
- Goal: >10 Io flybys with extended mission
  - Baseline: 6 Io flybys
- Flyby Conditions:
  - Initial altitudes will be higher (~500-1000 km) for navigation
  - Goal is to go as low as 100 km (esp. for NMS, Mag)
  - Higher inclination (non-equatorial) is desired for polar coverage
  - Repeat ~same solar longitude for change detection
  - Observe many eclipses (occur every Io day-- 42.5 hours)
    - Two high-resolution (~10 km/pixel imaging) eclipses per flyby
- End of mission: Impact Io for planetary protection

Tohil Mons



Minimal Payload

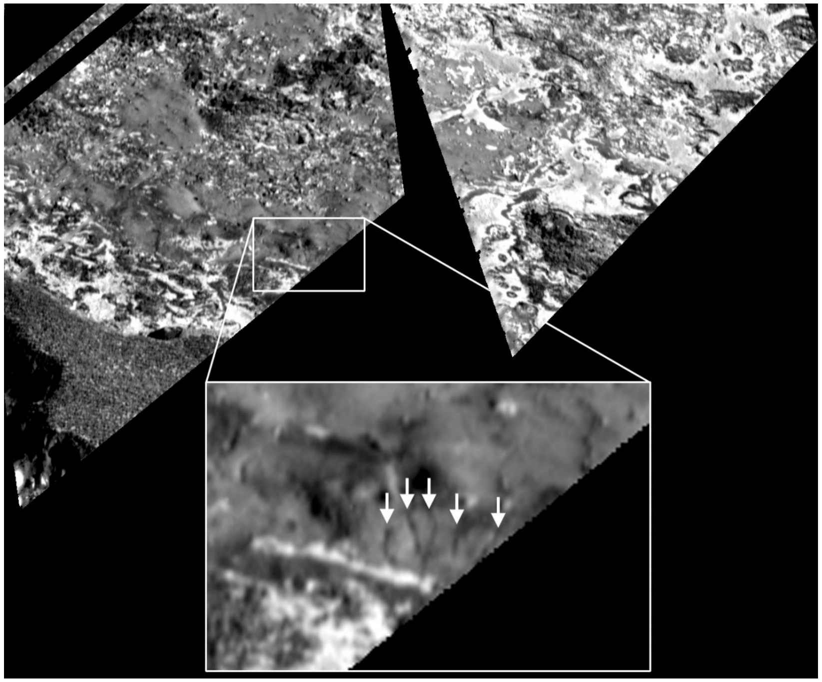
- Narrow-angle camera (~15 kg)
  - Monitor eruptions, measure peak lava temperatures, a few stereo images for topography; optical navigation
- Thermal mapper (~12 kg)
  - Map and monitor temperatures, heat flow pattern related to internal structure and tidal heating mechanisms
- Ion and Neutral Mass Spectrometer (NMS) (4 kg)
- Magnetometers (1 kg)
- Total payload mass ~32 kg (50 kg with 50% margin)



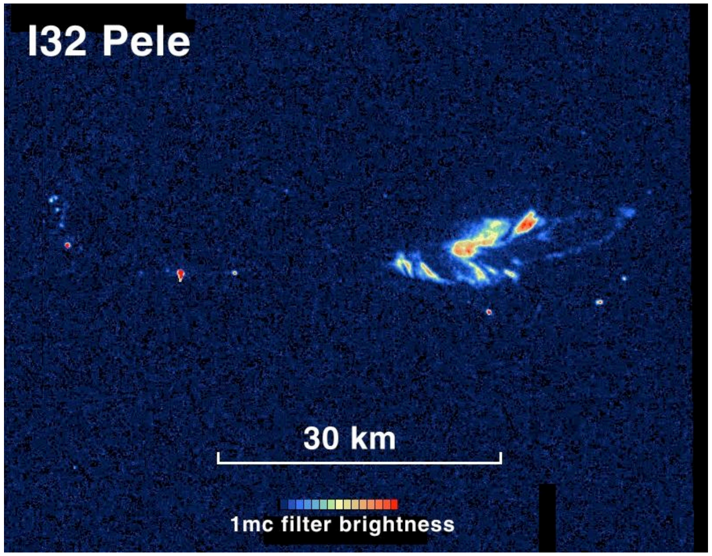
Narrow-Angle Radiation-hard Camera (RCam)

- Moderate resolution monitoring during approach and departure to/from Io; high resolution and (limited) stereo near closest approach
  - 10 urad/pixel gives 1 km/pixel from 100,000 km, 10 m/pixel from 1,000 km
  - LORRI on NH: 5 urad/pixel, 9 kg
  - LROC NAC: 10 urad/pixel, 5.5 kg
  - New CMOS focal-plane system, pushbroom and framing modes
  - New Digital Processing Unit (DPU) ~5 kg
- Simultaneous multispectral measurements for peak lava temperatures
  - 0.1 sec time differential could ruin the measurement because hot lava is so dynamic
  - Working on CMOS FPS with narrow (4 line) filters for nearly simultaneous color
- We do not consider ASRG-induced jitter to be a significant concern
  - Unless 1 ASC fails, but pause option is available

Highest-resolution GLL: 6 m/pixel



Lava glowing in the dark



RCam Concept

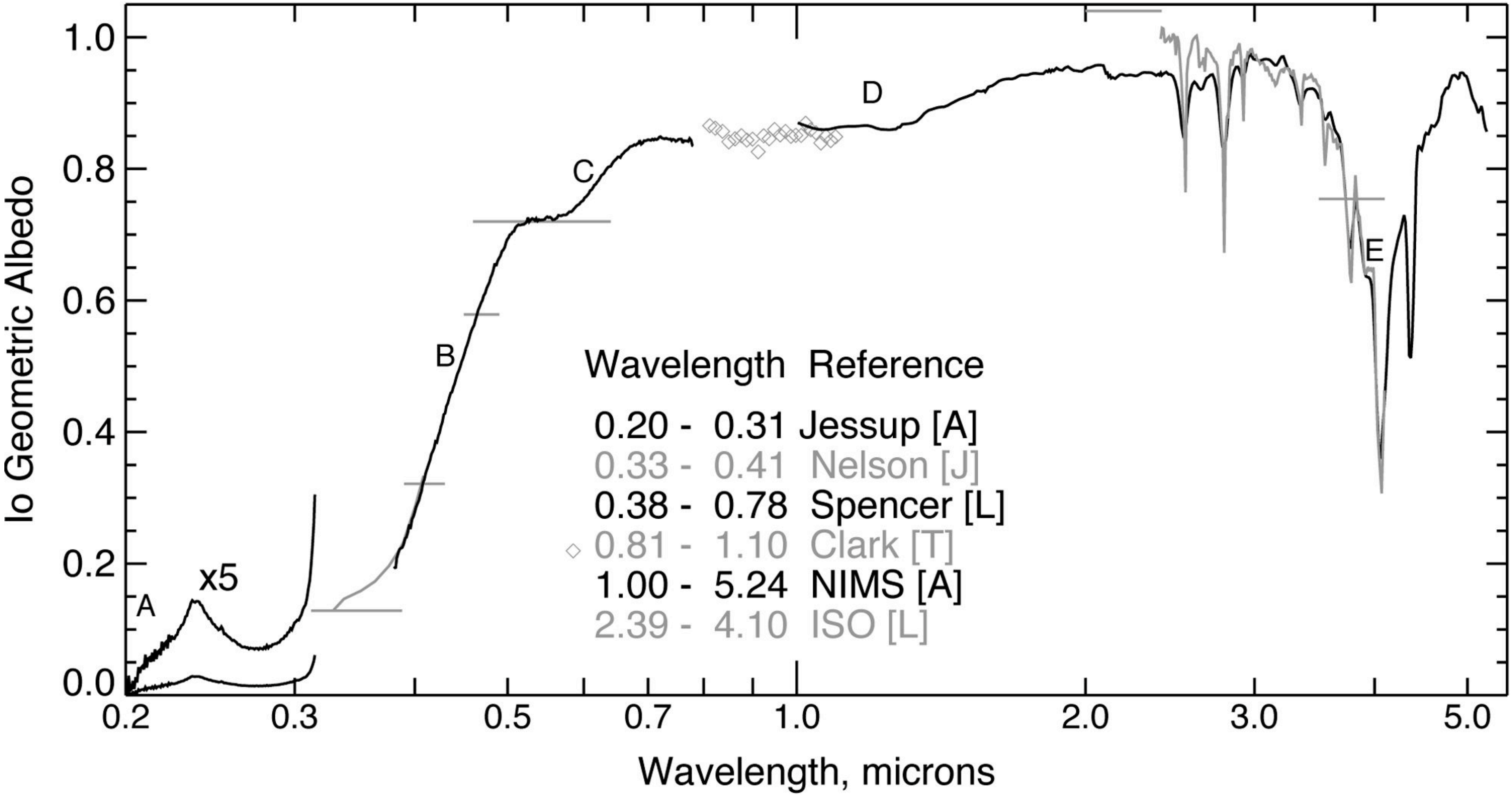
- 2000 x 2000 pixel CMOS arrays from Sarnoff (Jim Janesick)
- Excellent performance (~ 2 e- read noise) after 1-2 Mrad total dose (100 mils Al) (Janesick et al. 2008)
- Data readout extremely fast (240 Mb/s per ADC) to essentially eliminate radiation noise in images
- Can be used in either pushbroom mode (only way to get color) or framing mode (plume movies, optical navigation)
- PIDDP submitted to develop narrow (4-line) spectral filters and to further develop and radiation test the whole focal-plane system
- Separate (vaulted) digital processing unit (DPU)
  - Working with APL on design
- Digital Time-Delay Integration (dTDI) enables:
  - On-board super-resolution
  - Flexible slew angles
  - Sum interleaved color filters for nearly simultaneous color
  - Low read noise to image extremely faint targets with dTDI (Io plasma torus, Na cloud, Jupiter rings, Europa in eclipse)

NAC Color Filters

- Spectral range of backside-thinned CMOS detector with UV coatings is ~200-1000 nm (QE > 0.1)
- Threshold Mission:
  - Broadband blue-green, red, near-IR for lava temperatures and color images
    - Need interleaved 4-line filters for nearly simultaneous temperatures
  - UV (< 400 nm) for SO_2, plumes
- Consider for baseline Mission:
  - Spectrally narrow filters for Na, O, OH, S+
    - Can monitor Na, O, S+; search for OH escaping from Europa; unique viewing geometry (Io torus has never been seen at high inclination)
  - Silicate mineralogy bands near 1 micron (also helps avoid saturation of high-T hot spots)
  - Methane bands for Jupiter
  - H-alpha band for Jupiter lightning
  - S+ for Io plasma torus
  - More visible bands for S species and olivine
  - 200-300 nm UV band for ?? (auroral phenomena?)
  - Could have up to 15 filters with 64 dTDI lines on 2,000 x 2,000 array
    - Save at least 1000 lines for clear framing mode

Io disk-integrated spectrum

Spencer et al., 2004 Jupiter Book

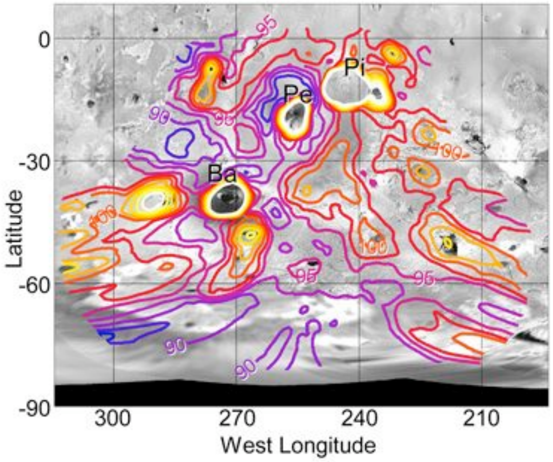


Wide-Angle Camera (WAC)

- It will be very difficult to get useful stereo imaging with just the NAC
  - Approach and departure geometries don’t provide good stereo separation.
  - Can’t slew spacecraft pointing near C/A fast enough in a 19 km/s flyby, unless range to Io is large, and risk of smear is high from rapid slews (via thrusters).
  - Combining ~100 m/pixel approach or departure image with ~5 m/pixel near C/A gives narrow strip (10 km) with just 100 m/pixel stereo scale.
- On wish list: WAC with ~25º FOV, same FPS and DPU as NAC
  - Each flyby can provide a stereo strip across Io (pole-to-pole) at up to 25 m/pixel (100 km range; 75 m/pixel DTM) and 10 m vertical precision.
    - Swath 50 km wide at 100 km range, widening towards poles
    - Pushbroom mode best for stereo separation but framing mode also possible with frame-frame overlap and 10-15 degree convergence angles.
  - Also provides better coverage of equatorial color and polar plumes
    - Pole-Pole 5,700 km at 50 m/pixel (average) in 4 colors: 912 Mpixels or ~ 3.6 Gbits compressed to 4 bpp.

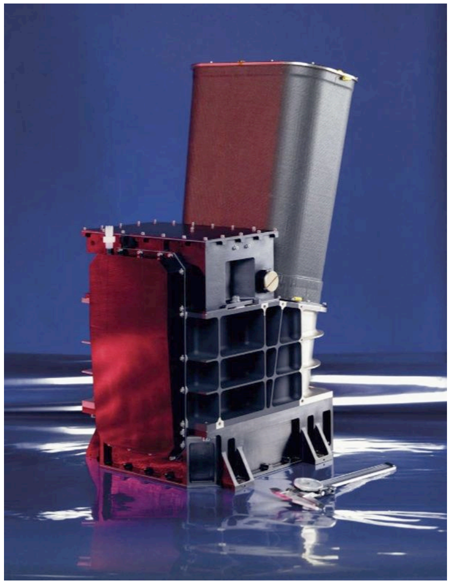
Thermal Mapper

- Threshold Mission: 3 bandpasses from ~2-20 microns to monitor volcanism and measure heat flow
  - constraint on interior properties and tidal heating
  - Io surface Ts range from 70 to perhaps 1600 K!
    - Mercury T range is ~90 to 700 K
- IVO in high-inclination orbit provides unique polar views not available from Earth or GLL or a likely Flagship mission.
- Thermal Emission Imaging System (THEMIS) is close to what IVO needs
  - 4.6 deg FOV, 250 urad/pixel, 1 km/pixel from 4,000 km
    - New 640 x 480 detectors: 1 km/pixel from 8,000 km; potentially 1000 x 800
  - weighs 11.2 kg, including vis; 10 IR bandpasses
- Baseline Mission:
  - Attempt thermal emission compositional studies
    - Emission features present in glass
    - Expect highly vesicular lava--little blackbody radiators eliminate emissivity variations--but overturning could expose dense lava, or some flows could be degassed and not too vesicular
  - Bandpasses for Jupiter monitoring (e.g., 5-micron hot/dry spots)
  - Consider optics design for compatibility with NAC slew speeds



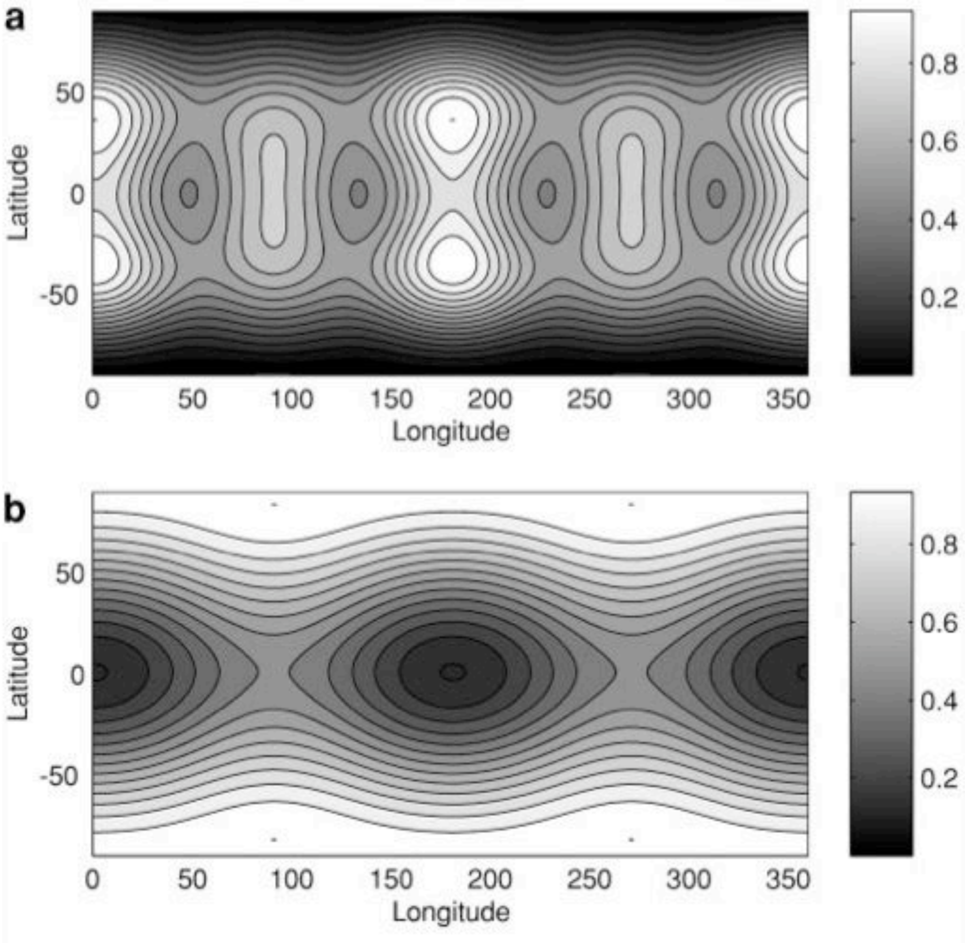
Nighttime T map from GLL PPR

THEMIS



Models for heat flow patterns

(Segatz et al., 1988; Ross et al., 1990; Tackley et al., 2001)



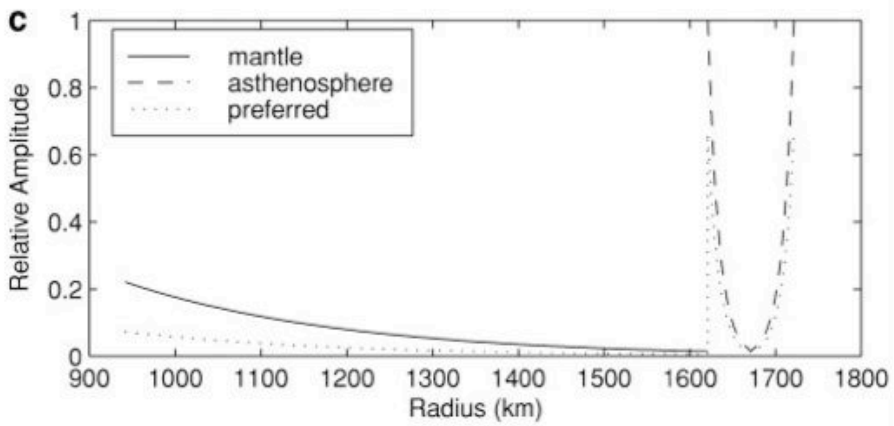
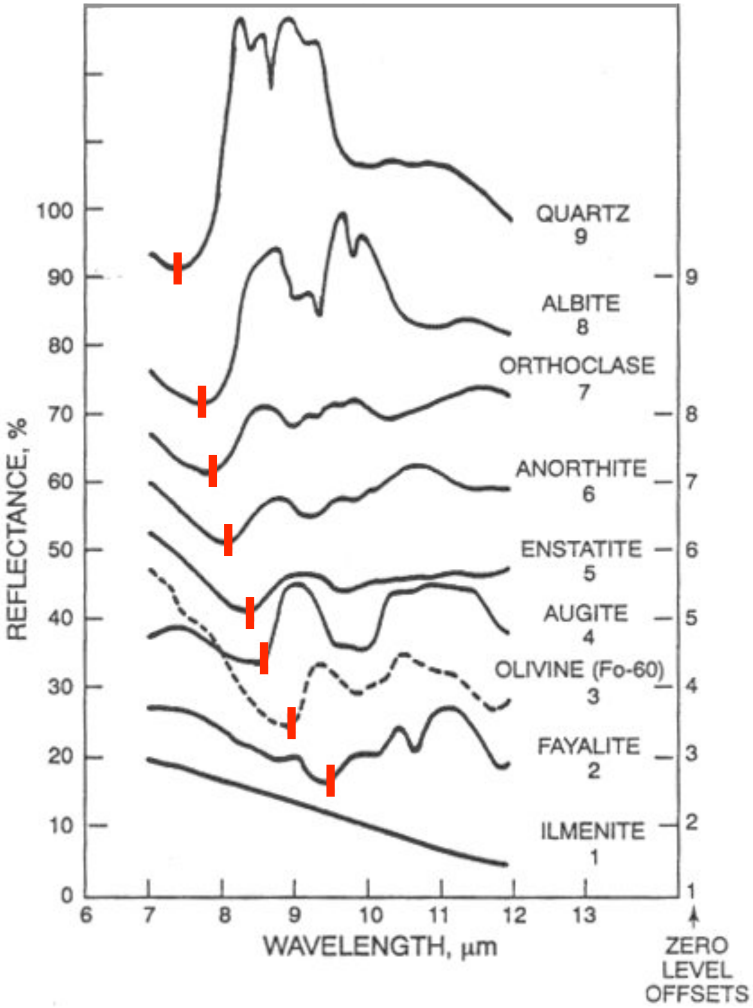


FIG. 1. Azimuthal distribution of heating for (a) asthenosphere and (b) mantle models, based on Segatz *et al.* (1988) and Ross *et al.* (1990). The sub- and antijovian points correspond to 0° and 180° respectively. (c) The radial distribution of heating for all mantle (solid line), all asthenosphere (dashed line), and preferred (combined) modes (dotted line). Curves have the correct relative amplitude.

The CF: Diagnostic of Composition

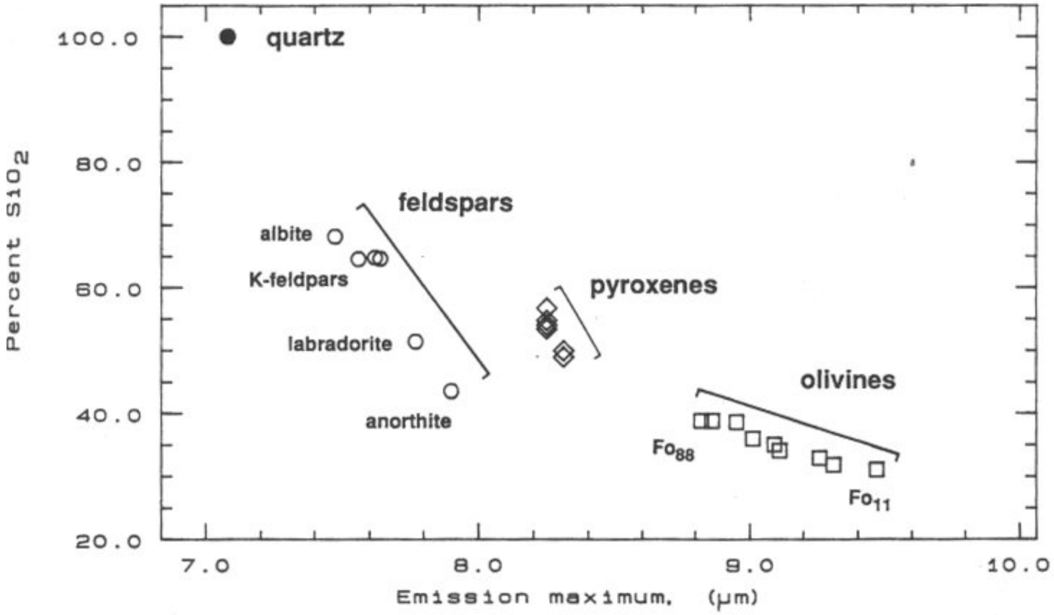
Mineral Powders in Air



The Christiansen Feature location and other features vary with silicate mineralogy

This relationship is well defined for mineral powders

Good independent confirmation of lava composition constraint from peak temperatures

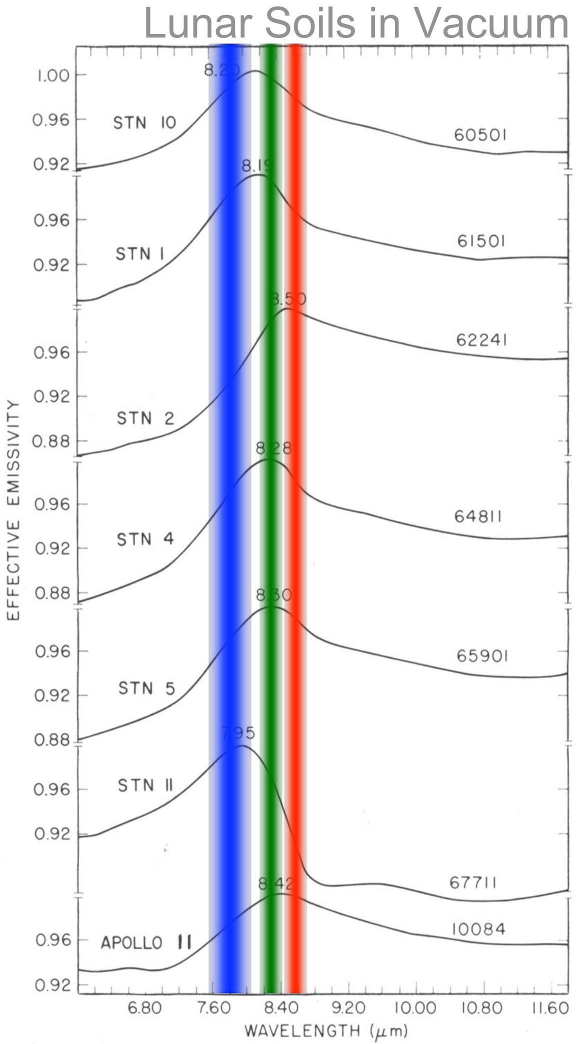


both after Nash et al, 1993

Thermal Mapper candidate bandpasses

(Up to 10 bandpasses)

- 2 micron band or as short in wavelength as possible for microbolometer detector
- 2 micron band with neutral density filter (NDF) to avoid saturation of hot lavas
- 5 micron band (Io Ts and Jupiter hot/dry spots)
- 5-micron band with NDF
- 3 bandpasses from 7-9.5 microns to define the wavelength of the Christiansen Frequency (CF) emission peak
- 1-2 bandpasses in 10-12 micron range for silicate mineralogy
- ~20 microns for background temperatures
- Attempt >20 microns for coldest polar temperatures?


Lunar Soils in Vacuum

after Salisbury et al, 1973

LRO Diviner bandpasses for CF

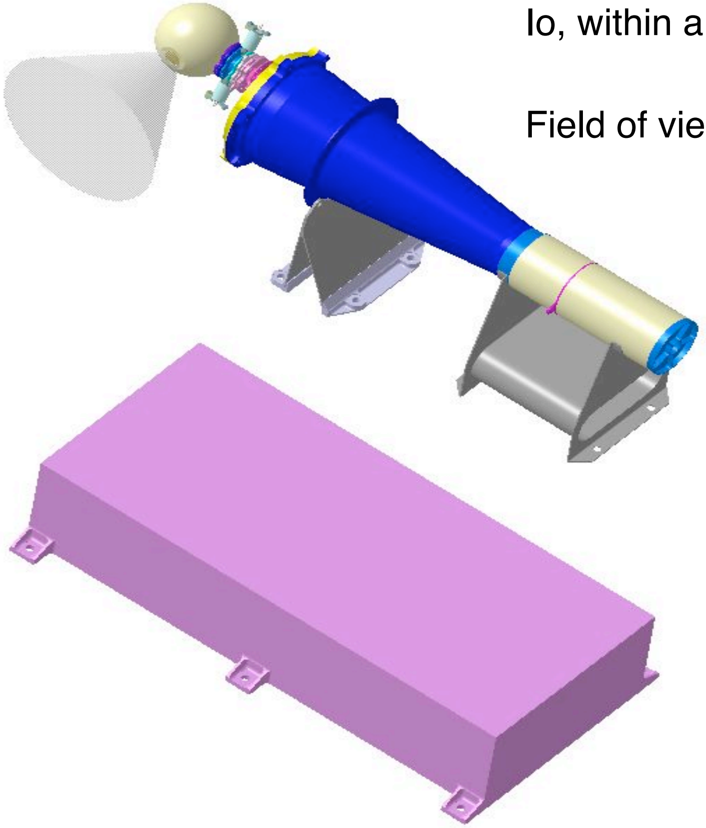
Ion and Neutral Mass Spectrometer (NMS)

Science Questions:

- What is spatial distribution of the major neutrals contributing to the Io Plasma Torus (IPT)?
  - Determines the energy input to the IPT.
  - Constrains models of the interaction.
- What is the gas composition of the volcanic plumes?
  - SO_2 and S_2 detected (Spencer et al.)
- What is the composition of the neutrals?
  - S/O ratio is critical in modeling.
  - What molecules are present (SO_2 for sure but NaCl, NaO, SiO_2)
- Is there a relationship between neutral density and volcanic activity?
  - Requires multiple passes - and some luck.
- Io‘s atmosphere
  - SO_2, SO, O_2, Na, K, O, NaCl (Lellouch et al., 1990, 1995, 1996, 2003; Bouchez et al., 1999; Postberg et al. 2006; de Pater et al. 2002)
  - What trace elements are present?
  - What is the temporal evolution, day-night dependence, leading-trailing side
  - What are mechanisms and rates of atmospheric loss?

NMS Sensor Head and E-Box

- **Dimensions**
  - Sensor: 100 mm x 365 mm
  - Electronics: 300 x 130 x 65 mm
- **Power**
  - Standby: 3 W
  - Operational: 9 W
- **Mass**
  - Sensor: 2.5 kg
  - Electronics and harness: 1.5 kg
- Mass spectra are recorded once every 5 seconds (flyby mode) that gives a direct science data rate of 19,200 bits/s.



Entrance of NMS has to point into ram direction at closest approach (CA) to Io, within a few degrees

Field of view cone is ±60°

NMS to be contributed by U. Bern--Nick Thomas, Peter Wurz and Swedish Institute of Space Physics--Martin Wieser and Stas Barabash

mass range 1-300 amu; M/∆M = 300 – 1000, increases with mass

NMS Prototype
P-BACE

- Polar-Balloon Atmospheric Composition Experiment (P-BACE) Instrument on MEAP mission
  - Test of the mass spectrometer on a stratospheric balloon flight around the north pole.

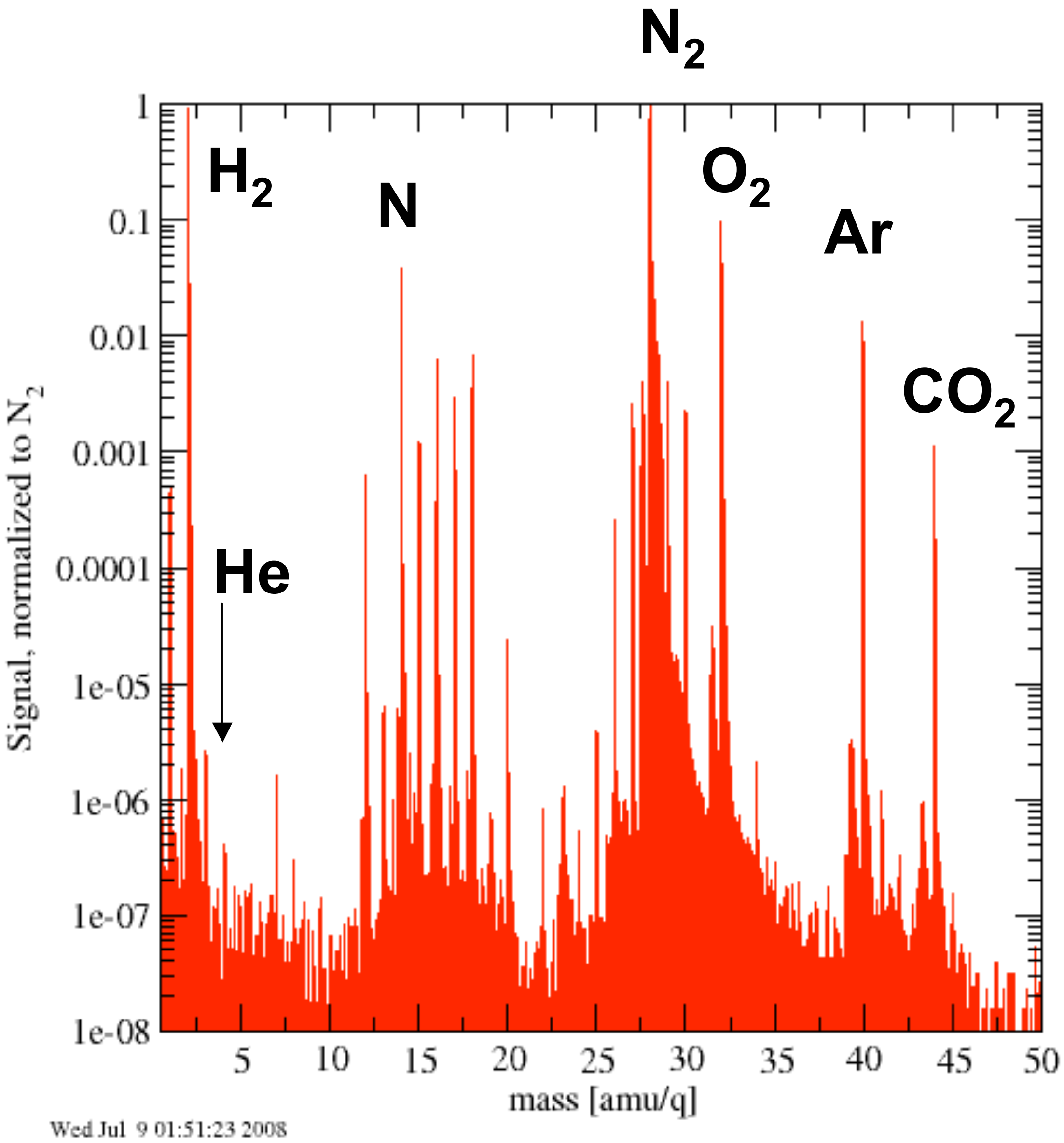
Image left:

- Drift tubes
- Reflectron

Image right:

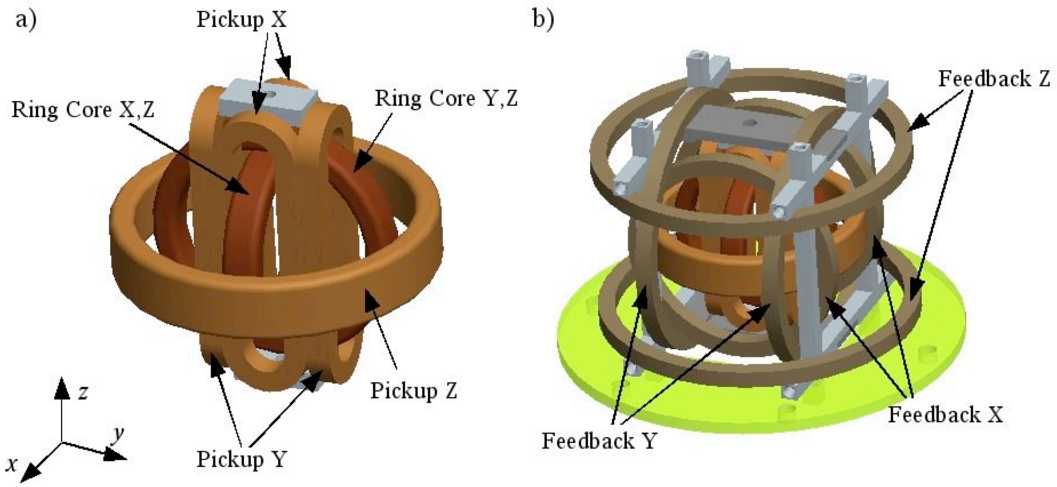
- Storage ion source
- Detector

P-BACE quick-look data



- Raw data
- No background subtracted
- Dynamic range: 6–7 orders of magnitude
- Mass range: 1–1000 amu/q
- Can even detect protons and H_2
  - Is Io really completely dry?

Fluxgate Magnetometers



Vector compensated fluxgate ringcore sensor
Heritage: Rosetta, Venus Express, Themis, BepiColombo

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	Eigenschaft.
Mass Budget	
- Sensors 2 x 75g	150g
- Tube	150g
- Thermal Cover:	100g
- Harness 60g/m x 2m	120g
- Boards 2 x200g	400g
Sum	**920g**
Power Budget	
For each sensor:	
- secondary	1W
- primary:	1.3W
Total (if both sensors are powered)	
- secondary	2W
- primary:	**2.6W**

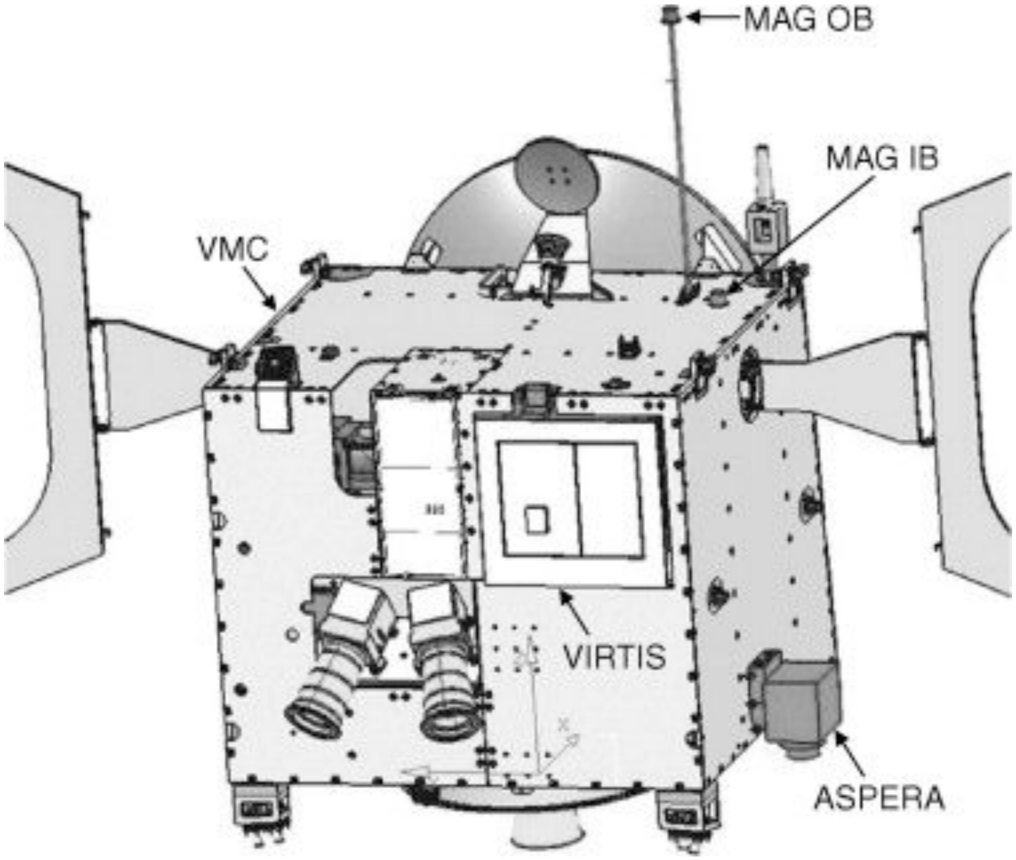
Mag Science Goals:

Characterize Jupiter’s magnetosphere (easy)

Place tighter constraints on Io’s internally-generated magnetosphere (hard)

Magnetometer on S/C

Can mount on 1-m bracket, no deployable boom

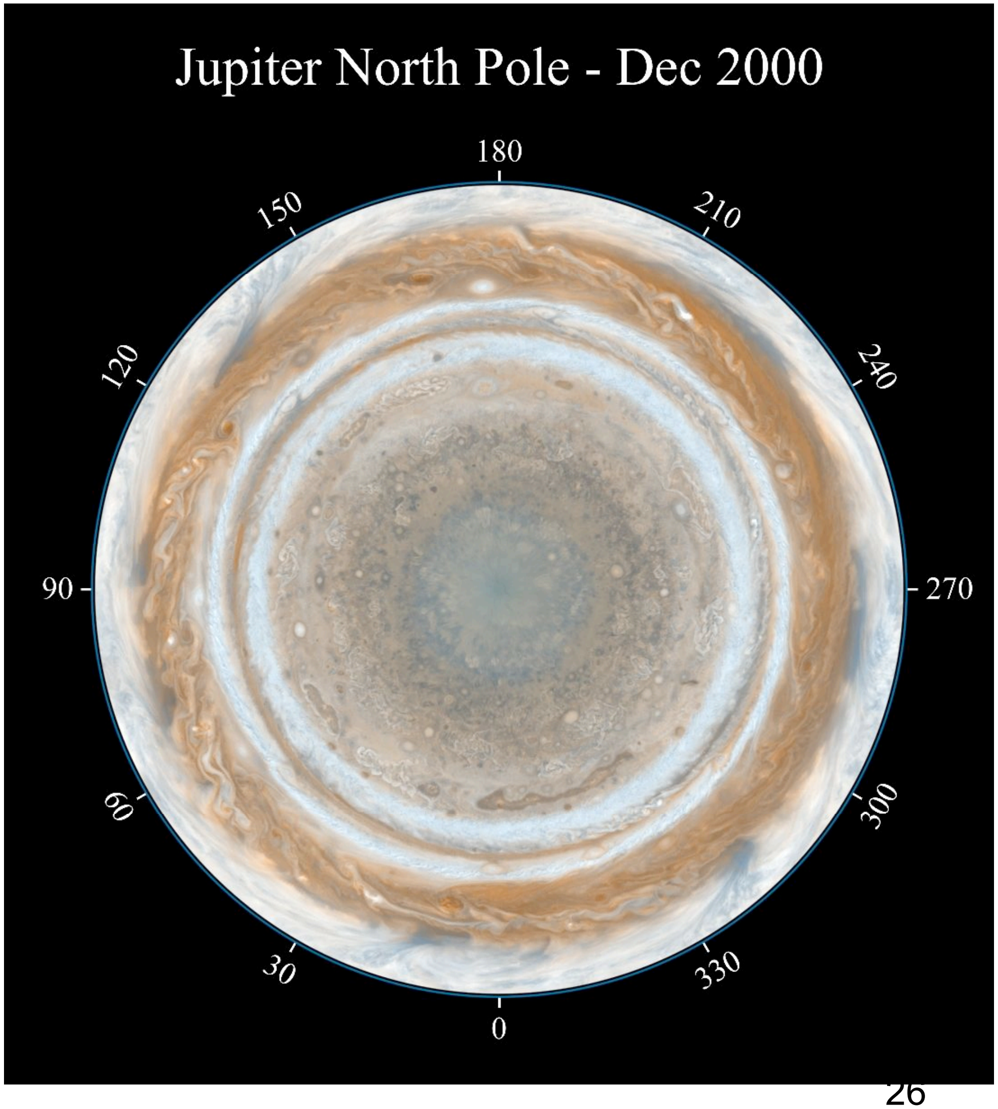


Venus Express S/C

Use of 2 magnetometers at different distances from S/C helps calibrate effects of S/C

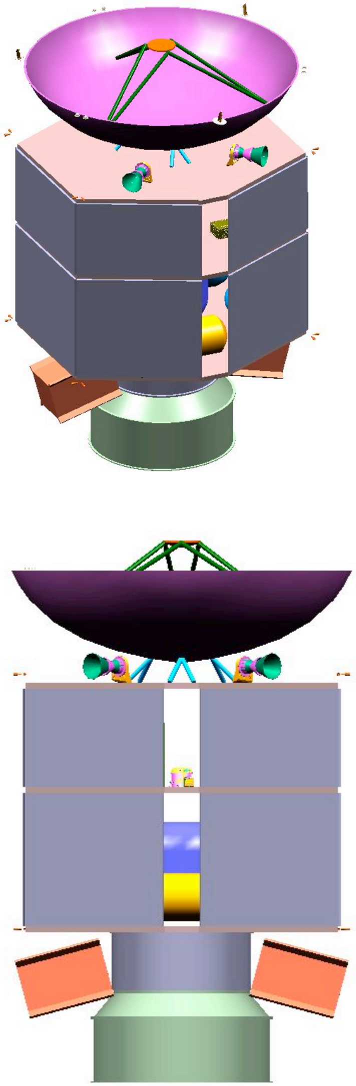
Jupiter System Science

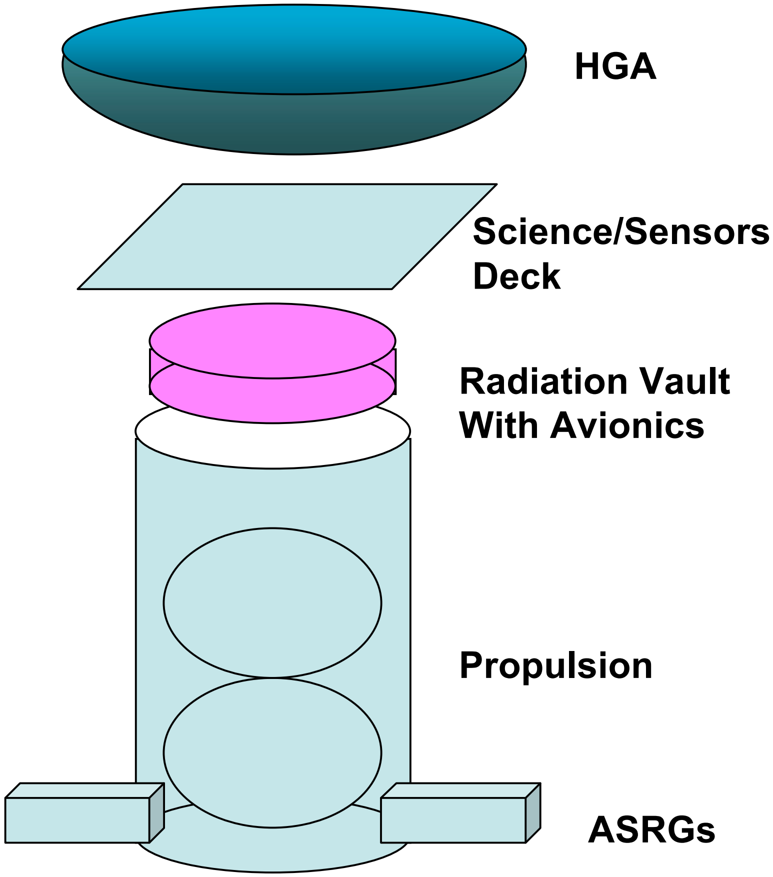
- Excellent monitoring of Jupiter's poles and rings and Io Plasma Torus from high-inclination orbit
  - Data volume limited
- Maybe some good opportunities to view small inner Moons
- Only distant views of icy Galilean Moons
  - Na, O, OH (?) around Europa
- Extended opportunity in first 200-day orbit after JOI
  - Jupiter overfills NAC FOV most of the time (< 7.15 x 10^6 km)



Configuration Progression

- deck with payloads on top and avionics on bottom
- enclosed in vault to shield from radiation



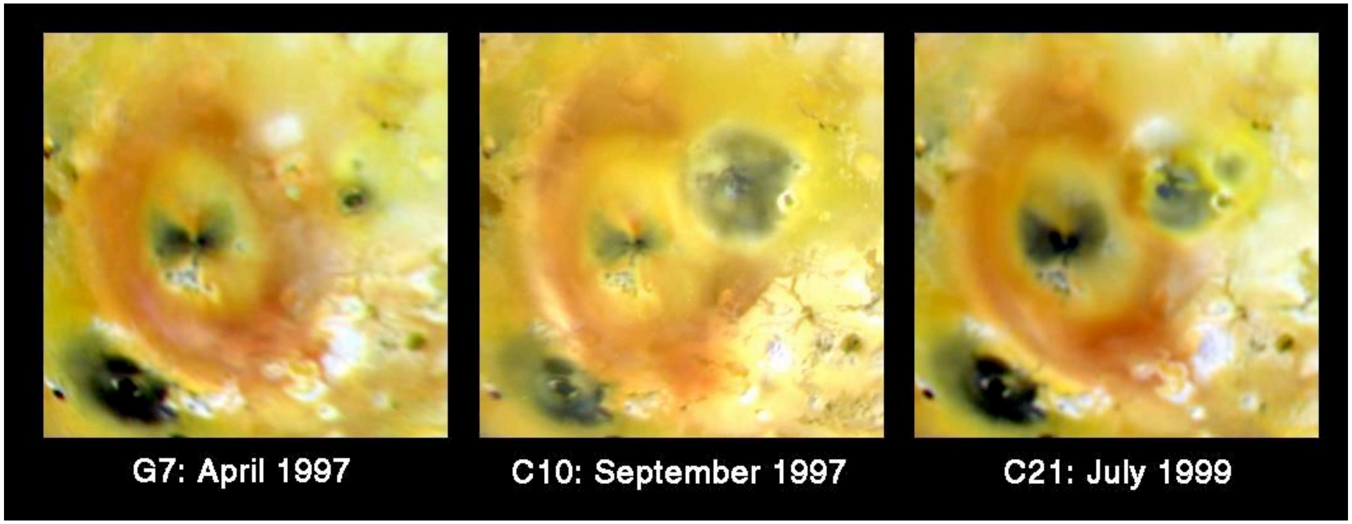


Mission Operations

- Science operations at University of Arizona
  - One interface to spacecraft team
- Spacecraft operations at TBD S/C manufacturer
  - Team X study assumed industry build with JPL management
- Launch in 1/2015, flybys of Venus, Earth (2x), arrival at Jupiter in 2021
  - Lunar cal on one Earth flyby
  - Magnetometer cal during an Earth flyby
  - Asteroid flyby?
  - Jupiter system science during approach and after JOI.
  - Io flyby
- Baseline: 6 additional Io flybys, ~1.5 yrs of operations after JOI
  - Collect up to 20 Gb of data within 1-2 days before and after each Io flyby, relay to DSN near apoapsis
  - Can return ~20 Gb/month via 34-m stations
    - Mostly NAC data with up to ~10:1 wavelets compression

How ASRGs enable IVO

- High data rate needed to achieve science
  - Dynamic Io must be observed over many timescales and at high spatial resolution and at multiple wavelengths to make major advances over Galileo
  - High data rate requires significant power; at 5 AU solar arrays would need to be very large
- Pointing flexibility needed to achieve science
  - Cannot keep solar arrays continuously pointed at sun without gimbals (and more power)
- Solar arrays degrade in radiation environment near Io
- Safe modes much easier



Study Progress

- Considerable work done in advance of Team X
  - Science requirements and payload defined
  - Representative interplanetary trajectory and Io tour developed by JPL
  - Spacecraft concept and grass-roots cost estimate completed
- Team X session at JPL Nov 4-6
  - Cost estimate: $471M (including launch vehicle) with full reserves
    - Assumption: Industry build with JPL management
    - Fully compliant with JPL design principles
  - Exploring areas to reduce cost ($450 M cap for the study)
- We will soon be ready to write final report; now looking forward to Discovery proposal
  - Need to pick spacecraft builder
  - We did this right by first understanding what we need
  - Payload development efforts are ongoing

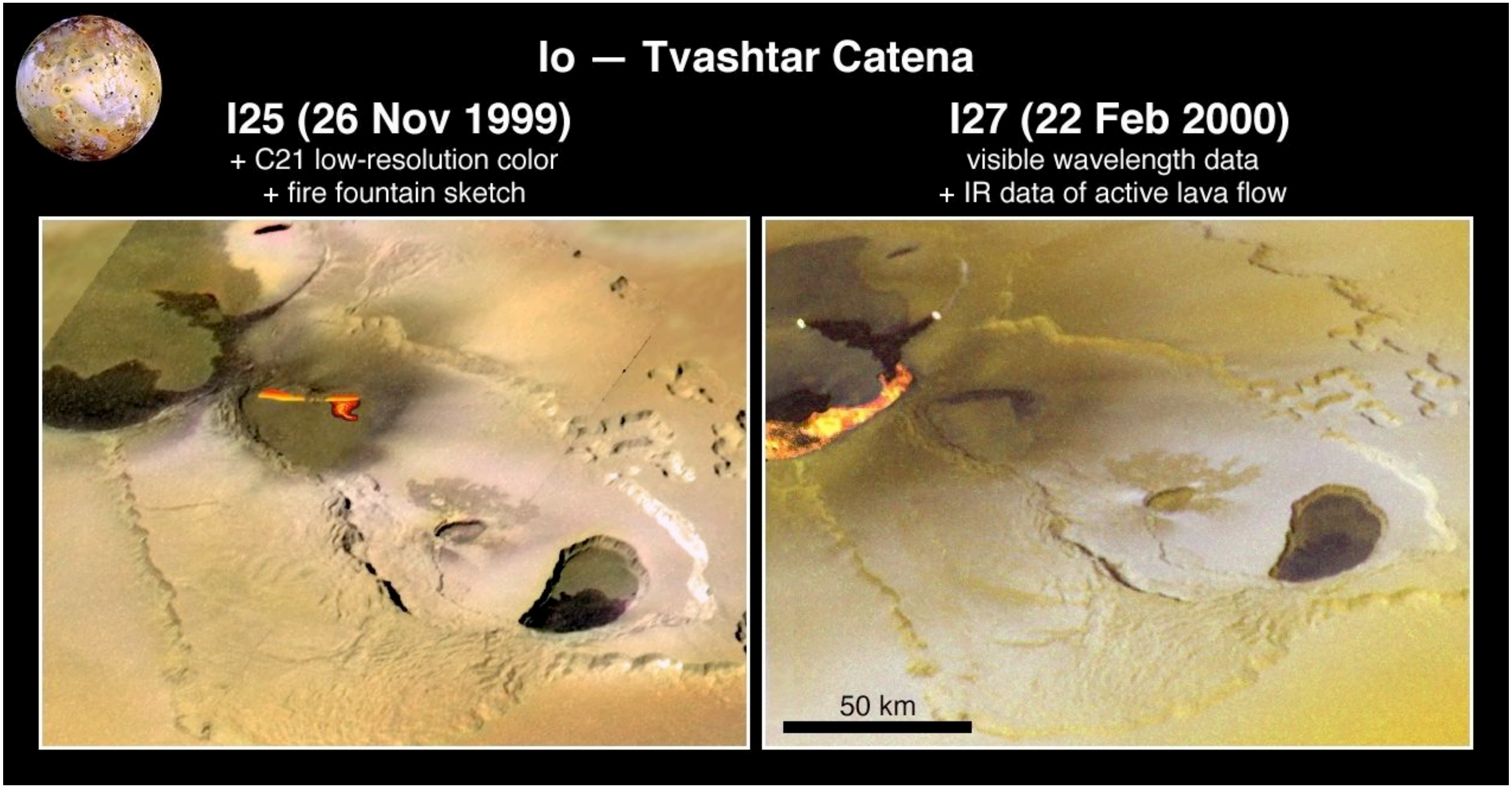
Issues

- Extending the ASRG life test
  - Radiation is the likely life-limiting factor, but we can easily boost the orbit to a longer period, even to 1 year, and perhaps extend the life test for a decade.
    - Opportunity to search for orbital evolution of Io (and Europa)
  - We can also move periapse away from Jupiter and Io, but Planetary Projection plan is to impact Io
- Cost
  - Need at least ~21M cost reduction from conservative Team X estimate
  - Actual Discovery 13 PI-managed cost cap TBD
- Risk
  - Replace single-string CDS with redundant system
    - We believe this can be done without increasing cost, via a different system than used by Team X
    - Will result in fully redundant S/C

Science Enhancement Options (or dreams)

- More spectral bandpasses on NAC and ThM
  - Greatest added science per $
- More DSN time (or 70-m coverage) and data volume for distant monitoring (Jupiter, torus, rings), if power available.
- Asteroid flyby (good dress rehearsal for Io flybys)
- Investigate how to detect or place tighter constraints on Io's intrinsic magnetosphere
- Useful gravity science with MGA?
  - HGA not pointed at Earth when we want to observe Io
- Fly 2 NMSs to get data during approach or departure from Io
  - First NMS oriented orthogonal to remote sensing--ram direction at C/A
- Add wide-angle camera for equatorial mapping and stereo near C/A
  - Can use same FPS design and actual DPU as NAC
  - Or 2 cross-strapped DPUs for redundancy
  - Nick Thomas (U Bern) may contribute optics
- Add NIR spectrometer for mineralogy
  - But fresh silicate lavas very glassy
  - Foreign contribution possible
- Add EUV spectrometer for torus and/or near-UV for atmosphere/plume gasses
  - Probably too expensive, foreign contribution unlikely
- Energetic Particle Detector for science and future exploration
- Recommend use of SALMON to add an experiment?
- Student-built Dust Detector or other experiment for ~$3M.

- Science Team
  - Must limit Co-Is to those essential during development and cruise phases
  - Participating Scientist program at Jupiter



Io — Tvashtar Catena

I25 (26 Nov 1999)
+ C21 low-resolution color
+ fire fountain sketch

I27 (22 Feb 2000)
visible wavelength data
+ IR data of active lava flow

Does IVO have a chance in Hell of success?

Yes, because:

- Io is a world of fire and brimstone.
- With 1/2015 launch we arrive at Jupiter when Alfred is 66 yrs old.
- Discovery #13 must be the right opportunity to send a mission to hell.
  - (Don't tell Venusians)