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

- Orbit inclined ~45° 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
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 flythrough New Years Eve 2028!
• 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

- Earth
- Io
- No terrestrial equivalent

Pahoeohoe flows
Lava lake
Open channel flows
Io outburst

10 Ma Pomona Flow Field, USA
Longest mapped ancient lava flow on Earth

1983–current Puu Oo Flow Field, Hawaii
Longest currently active lava flow on Earth

1783–1784 Laki Flow Field, Iceland
Longest lava flow on Earth documented while active

Amirani-Maui Flow Field, Io
Longest active lava flow in the Solar System

Pahoehoe flows
Lava lake
Open channel flows
Io outburst

Kilauea
Prometheus
Kupaianaha
Pele
Mauna Loa
Pillan
Loki 1990
DISTRIBUTED HEATING
“deep mantle”

lower-\(T\), smaller eruptions

low heat flux

Deep, partially-molten mantle

higher-\(T\), larger eruptions

high heat flux

SHALLOW HEATING
“asthenosphere”

Thin, shallow, molten layer

high heat flux

higher-\(T\), larger eruptions

lower-\(T\), smaller eruptions

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 1600° 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)

Small lava droplets can cool by 600º C in 1 second!
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
<table>
<thead>
<tr>
<th>Eruption type</th>
<th>Location</th>
<th>Thermal characteristics</th>
<th>Short-timeframe change</th>
<th>Long-timeframe change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ponded flow (stagnant flow)</td>
<td>Fixed</td>
<td>High to low flux density. High to low colour temperature.</td>
<td>Fixed location, cooling with time like a lava flow.</td>
<td>Thermal emission follows predictable cooling curve to extinction or renewal.</td>
</tr>
<tr>
<td>Insulated and tube fed flows (pahoehoe flows)</td>
<td>Wandering, persistent thermal source.</td>
<td>Low flux density. Low colour temperature.</td>
<td>Source increases in area in downslope direction.</td>
<td>Source migrates and increases in size with time. Lava tubes form.</td>
</tr>
</tbody>
</table>

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 $\text{Re}(k_2)$ 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

![Sun Europa SC Angle (deg)](image)

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
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 extraterrestrial 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.

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, tectonics, tidal dissipation, solar atmosphere 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 extraterrestrial 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:

<table>
<thead>
<tr>
<th>Objectives (Gain understanding of)</th>
<th>Key Measurements</th>
</tr>
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<tbody>
<tr>
<td>1. Io is active volcanism</td>
<td>High-resolution thermal imaging at Io’s thermal altitudes</td>
</tr>
<tr>
<td>2. Nature of Io’s interior &amp; implications for tidal heating</td>
<td>Measure peak temperatures and temperatures &amp; electromagnetic radiation from mantle-magma interaction.</td>
</tr>
<tr>
<td>3. Nature of Io’s atmosphere &amp; unique interactions</td>
<td>Image &amp; analyze the Io’s interaction with solar and stellar activity.</td>
</tr>
<tr>
<td>4. Connections between Io’s volcanism &amp; tectonics</td>
<td>Measure mass surface &amp; temporal variability of Io’s surface &amp; monitor changes in Io’s interior.</td>
</tr>
<tr>
<td>5. Io’s mass loss &amp; mass loss characteristics</td>
<td>Measure Io’s mass loss &amp; monitor changes in Io’s interior.</td>
</tr>
</tbody>
</table>

Mission Overview:
Launch May 29, 2021
- JU/EGPS (Earth gravity assist) trajectory, asteroid flyby opportunities
- Jupiter orbit insertion (JOI) in February 2026 with 500 km encounter (IO) and capture into orbit inclined 42° relative to Jupiter’s equator
- Eight additional Io encounters over 6 weeks 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 keV at 100 m keV for 6-keV electrons) in Io’s interior by monitoring Io’s surface
- Collected 20 Gb science data per encounter: 100 times the Io data from the 8-year Galileo tour: playback near apastasis
- Encounters last ~1 week, including global monitoring and four to eight observations
- Near-polar approach to and departure from Io is ideally suited for studying polar regions, key to testing tidal heating models

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
- Imaging of high-temperature activity on north side of Io in 25 colors at <100 m/pixel to measure local lava temperatures
- Near-global (<20%) TMM coverage at 0.1-10 km/pixel to map Io’s heat flow and monitor volcanism
- 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 (800 spectra) near Io closest approach (CA) and segments away from Io
- Monitoring of Io, Europa, and Jupiter system

DISTRIBUTED HEATING - SHALLOW HEATING “deep mantle”
- Better plumes with larger excavations, thicker crust
- Better plumes with larger excavations, thicker crust

Thanks for listening!