# THE *IO VOLCANO OBSERVER (IVO)*.

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**Introduction:** ***The Io Volcano Observer (IVO) will transform our understanding of fundamental planetary processes.*** Io is the best place to study the effects of tidal heating and volcanism, key processes that shaped terrestrial planets, icy ocean worlds, and extrasolar planets. Caught in the Laplace resonance with Europa and Ganymede, Io is the most tidally heated world in our Solar System, with a global average heat flow more than 20 times greater than on Earth today. This heat drives hundreds of active volcanoes that sustain an atmosphere and the Io plasma torus. Io is the ideal planet-scale laboratory to study the causes of extreme volcanic activity and provides our best window into the volcanically hyperactive youth of all rocky planets.

A Keck Institute for Space Studies report [1] provided an updated synthesis of Io science priorities. Central to these priorities is the need to distinguish between end-member models for the abundance and distribution of melt in Io's mantle [2]. ***"Follow the heat"*** is our mantra to understand the origins and migration of magma from Io's interior, through its lithosphere (rigid outer layer), and onto the surface. This understanding is essential to answering the question of how and where tidal heating drives melt production and controls the unique heat-pipe tectonics of Io, an analog for the early terrestrial planets. Io's high-temperature eruptions may help us to understand Earth's Hadean (>3.8 Gyr ago) environment.

***IVO provides unique and essential contributions to top priority planetary science themes***. While other missions and telescopes provide valuable distant monitoring of Io, they cannot answer key questions about Io's interior and tidal heating; *IVO*'s close flybys, polar views, and in situ measurements are required. *IVO* measurements are key to understanding Io's energy and volatile budget, the coupled evolution of the Galilean satellites, and processes shaping tidally heated worlds across our Solar System and beyond.

***IVO acquires critical Jovian system observations that other current and planned missions (Juno, JUICE, and Europa Clipper) will not obtain.*** Both completed Decadal Surveys recognized that Io requires a dedicated mission. Io science is essential to understand the tidal heating of Europa, Ganymede, and other ocean worlds [1, 3] improving interpretation of results from those missions. Now is the ideal time to develop *IVO* for launch in early 2029 (see figure at right).

### *IVO is an exciting low-cost mission.*

- *IVO* addresses all seven Decadal Survey objectives defined for a New Frontiers-class Io mission.
- *IVO* uses multiple complementary measurements for robust testing of well-developed hypotheses.
- *IVO* uses mature technologies and instruments, leveraging NASA investments in several recent missions.
- Implementation risk is low due to the simple spacecraft design, the experienced team, and high margins.

### Why Now?

- **High-priority Science:** *IVO* will close critical gaps in our knowledge of tidal heating, a process identified in the Decadal Survey as being crucial to understanding the evolution of habitable worlds.
- **Multi-Mission Science**: *IVO* operating with *Europa Clipper* and *JUICE* creates an observatory super-mission to study the intertwined tidal heating, orbital evolution, and magnetospheric processes of the Jovian system.
- **Optimal Timing**: Launch in early 2029 will maximize *IVO* science return by capitalizing on the teams, tools, and support for missions in development (*Europa Clipper*, *JUICE*, *DART*). The 2029 launch also assures resources for a substantial (10 orbit) extended mission.
- **Programmatic Flexibility:** The 2020 CAPS [4] report found *IVO* to be "functionally identical" to the NF5 *Io Observer* mission. Selection of *IVO* now would remove *Io Observer* from consideration and enable NF5 to focus on missions that require the NF cost cap.

### *IVO contributes to all three crosscutting themes identified by the Decadal Survey.*

**Workings of Solar Systems**

- Investigates the active interaction of chemical and physical processes that shaped the solar system.
- Supports studies of the origin and evolution of volatiles.
- Supports studies using the Jovian system as a model for extrasolar planetary systems.

**Planetary Habitats**

- Investigates the Laplace resonance that drives tidal heating within the Io-Europa-Ganymede system, and the mass transfer of oxidants and S-species from Io to Europa, both of which may sustain habitability.

**Building New Worlds**

- Advances our understanding of the early evolution of the Moon and inner planets, including Hadean Earth.

### *IVO Science Objectives will determine:*

***A1***. The degree and distribution of melt in Io's mantle.

***B1***. Io's lithospheric structure.

***B2***. Where and how Io is losing heat.

***C1***. Io's orbital evolution.

***C2***. The current rate of volatile loss from Io.

**Mission Overview:** *IVO's* prime launch window is Jan 2-28, 2029, allowing Mars and Earth gravity assists, with arrival at Jupiter on Aug 2, 2033. A backup launch in Feb 13 to Mar 7, 2030 would arrive Aug 10, 2034. The first Io encounter (I1) occurs before Jupiter orbit insertion, and 9 additional Io encounters (I2–I10) are completed in 3.5 yrs. *IVO*'s orbit is inclined ~45° to the plane of the Jupiter system, with time between encounters ranging from 78–260 days and velocities relative to Io of 17–19 km/s. This combination of inclined orbit and rapid flybys keeps the total ionizing radiation dose of the mission surprisingly low, ~15 times less than that of *Europa Clipper* and half that of *Juno*. The tour allows ample time to return 400 Gb of science data, 2000 times the total Io data from *Galileo*.

The tour and encounter geometries are carefully designed to achieve the science objectives (Box 3). Io's elliptical orbit precesses around Jupiter, allowing encounters near the moon's periapsis and apoapsis (twice each for robust gravity science), and driving the 3.5-year tour duration. *IVO* also encounters Io in-between periapse and apoapsis, ideal for measuring the diurnal libration amplitude. Migration of subsolar longitude plus Jupitershine imaging enable nearly global (>80%) mapping at <300 m/pixel (visible), plus near-global (>70% day and night) thermal IR mapping at <2.5 km/pixel.

**Science Enhancement Options** (SEOs) are proposed for (1) inclusive student and early-career onboarding; (2) coordination of Earth-based monitoring of Io; (3) a close flyby of a 10-km asteroid in the important Themis family; (4) Jupiter system science; and (5) an extended mission. Large margins on fuel and the radiation design should enable ***an extended mission with ~10 additional Io encounters over ~2 years***.

**Science Experiments:** The Baseline Mission supports six science experiments and we are proposing Student Collaboration and Technology Demonstration Option (TDO) instruments.

The **Narrow-Angle Camera (NAC)** provided by APL combines the rad-hard electronics and detector of the Europa Imaging System [5] on *Europa Clipper* with more compact optics. It includes 12 spectral bands for monitoring the colorful surface, plumes, auroral, and hot-lava emissions.

The **Thermal Mapper (TMAP)**, provided by the German Aerospace Center (DLR) with heritage from MERTIS [6], includes microbolometer and radiometer arrays with ten bandpasses to map heat flow, hot spot energetics, and determine lava composition.

Both NAC and TMAP are mounted on a ±90° pivot; combined with spacecraft (S/C) rotation about its Z axis, they can be pointed at any target while maintaining sun-pointing of the solar arrays.

The **Dual Fluxgate Magnetometer (DMAG)** provides low-noise sensors with extensive flight heritage from the University of California Los Angeles (UCLA), while the **Plasma Instrument for Magnetic Sounding (PIMS)**, identical to the instrument built by APL for *Europa Clipper* [7], measures ion and electron plasma. DMAG and PIMS, together with carefully designed encounters and lab measurments, will characterize Io's electrically conducting interior [8].

**Gravity Science (GS),** led by the Jet Propulsion Laboratory (JPL), uses 2-way Doppler tracking and precision ranging to measure tidal deformation and Io's orbital evolution [e.g., 9].

The **Ion and Neutral Mass Spectrometer (INMS),** provided by the University of Bern (UBE), will provide the first comprehensive, direct detections of neutral species near Io [10].

The **Student-Collaboration Wide-Angle Camera (SWAC)** will provide large-format (2048 × 4096 pixel) framing images with stereo overlap. The TDO **Reflective UV Spatial Heterodyne Spectrometer (RUSHeS)** covers 115–175 nm with $\lambda/\Delta\lambda > 10^5$ [11]. Both instrument options are from the University of Arizona (UA).

All science experiments will collect data simultaneously during Io encounters, without pointing conflicts. The spacecraft will operate in Jupiter orbit with the high-gain antenna (HGA) and solar arrays pointed to the Earth/sun except for 20–30 minutes of the closest approach period of I2–I10 and occasional calibration maneuvers. At Io closest approach of I2-I10, the remote sensing instruments point to Io's nadir while keeping the solar arrays obliquely illuminated. This orientation is best for remote sensing, optimal for INMS and PIMS, and acceptable for GS via the low-gain antenna for Doppler tracking.

**References:** [1] deKleer, K. et al. (2019), https://kiss.caltech.edu/workshops/tidal_heating/tidal_heating.html. [2] McEwen, A. S. et al. (2020) *LPSC 51*. [3] Dirkx, D. et al. (2017) *Planet. Space Sci.*, *147*, 14–27. [4] CAPS (2020) *Options for the Fifth New Frontiers Announcement of Opportunity. Washington, DC: The National Academies Press*. [5] Turtle, E. P., et al. (2019) *LPSC 50*. [6] Helbert, J., et al. (2008) *Proc. SPIE*, *7082*, 70820L. [7] Grey M., et al. (2018) *2018 IEEE Aerospace Conference*, pp 1-15. [8] Khurana, K. et al. (2011) *Science*, *332*, 1186–1189. [9] Park, R. S., et al. (2011) *Geophys. Res. Lett.*, *38*, L24202. [10] Wurz, P. et al. (2021) this conference. [11] Harris, W., and J. Corliss (2014) *Proceedings of the SPIE, 9144*, Article ID 91442Y.