THE *IO VOLCANO OBSERVER (IVO)*: FOLLOW THE HEAT.

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Introduction: The *IVO* mission has been proposed previously [1] but has been re-focused in 2019 towards understanding tidal heating as a fundamental planetary process. Using our slogan "Follow the Heat", *IVO* will determine how heat is generated in Io's interior, transported to the surface, and lost to space, primarily via active volcanism.

Tidal Heating: Tidal heating is key to the evolution and habitability of many worlds across our Solar System and beyond. However, there remain fundamental gaps in our understanding, which motivated a Keck Institute of Space Studies workshop [2]. The Laplace resonance between Jupiter's moons, Io, Europa, and Ganymede, results in extreme tidal heating within Io [3], and this system provides the greatest potential for advances in the next few decades. The easily observed heat flow of Io, from hundreds of continually erupting volcanoes [4], makes it the ideal target for further investigation, and the missing link along with missions in development (e.g., *Europa Clipper* and *JUICE*) to understand the Laplace system.

The KISS study [2] identified five key questions to drive future research and exploration: (Q1) What do volcanic eruptions tell us about the interiors of tidally heated bodies? (Q2) How is tidal dissipation partitioned between solid and liquid materials? (Q3) Does Io have a melt-rich layer, or "magma ocean", that mechanically decouples the lithosphere from the deeper interior? (Q4) Is the Jupiter/Laplace System in equilibrium (i.e., does the satellite's heat output equal the rate at which energy is generated)? (Q5) Can stable isotope measurements inform about long-term evolution?

A promising avenue to address these questions is a new spacecraft mission making multiple close flybys of Io, combined with research and analysis motivated by the mission. *IVO* will be able to address all of these questions, while still within the constraints of NASA Discovery program. *IVO* will characterize volcanic processes (Q1); test interior models via a set of geophysical measurements (coupled with laboratory experiments and theory; Q2 and Q3); measure the total heat flow and tidal deformation of Io (Q4); and measure stable isotopes in Io's atmosphere and plumes (Q5). No new technologies are required for this mission, and this mission leverages advances in radiation design and solar power realized for *Juno*, *Europa Clipper,* and *JUICE*.

What is the Distribution of Melt within Io? This question must be answered to understand where and how tidal heat is generated. We plan to test four end-member models (Table 1), although combinations of these models are possible. The current evidence for a magma ocean in Io comes from *Galileo* magnetic induction data, and suggest at least 20% melt [5], although this has been debated [6]. *IVO* will provide a definitive result from multiple flybys with optimal geometries and plasma measurements [7]. *IVO* will make other measurements (k_2, libration) to provide independent tests for the presence of a magma ocean.

Table 1. Tests for Io's Melt Distribution

Model:	Tidal k_2:	Libration amplitude:	Magnetic induction:	Volcanism:
Solid body dissipation in deep mantle	low	low	weak	Polar concentration
Solid body dissipation in asthenosphere	low	low	weak	Equatorial concentration
Magma ocean	high	high	strong	Uniform, high-T
Interconnected melt and solids	low	low	strong	Uniform, high-T

Mission Architecture: The basic design is similar to previous *IVO* concepts [1]. The spacecraft will orbit Jupiter at an inclination of ~45°, minimizing total radiation dose to ~20 krad per flyby, and *IVO*'s total dose over 10 orbits will be less than one tenth that of *Europa Clipper*. The geometry of each Io encounter (Fig. 1) has been carefully designed to accomplish the objectives listed below.

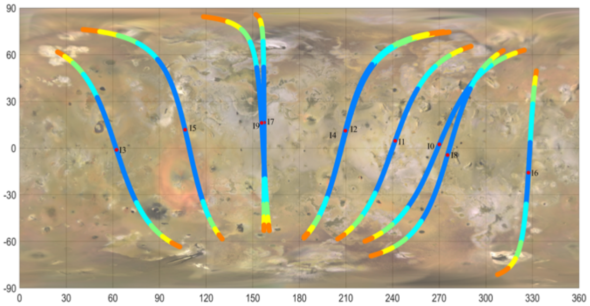

Fig. 1 Plot of groundtracks over Io during closest approach, color-code by range (blue indicates <1000 km).

Science instruments will include cameras nearly identical to those of the Europa Imaging System [8], the Plasma Instrument for Magnetic Sounding [9], dual fluxgate magnetometers from multi-mission heritage at UCLA, a thermal mapper with heritage from *BepiColombo* [10], and a neutral mass spectrometer in development for *JUICE* [11].

Science Questions: Key science questions IVO will address are: **(A)** How and where is tidal heat generated, and what is the melt distribution within Io (Table 1)? **(B)** How is tidal heat transported to the surface, and how is it lost at the surface? **(C)** How has Io evolved with time, and are the orbit, volatiles, lithosphere, and interior in a steady state?

Key Measurements:

Astrometry of Io's orbit: This is a fundamental constraint on tidal heating of the total system along with comparable measurements of Ganymede (*JUICE*) and Europa (*Europa Clipper*) [12]. The *Galileo* mission did not contribute much to astrometry due to failure of its high-gain antenna.

Measure amplitude of k_2 tidal Love number: Tidal k_2 will be much larger if Io has a fully liquid magma ocean, decoupling the lithosphere [13]. A set of four *IVO* orbits are designed to optimize this measurement.

Measure Io's libration: The libration amplitude will be much larger if a magma ocean detaches a rigid lithosphere [14]. Two *IVO* orbits are designed to optimize this measurement.

Multi-frequency magnetic induction: A set of at least 8 *IVO* orbits will measure the global average lithospheric thickness and global conductivity (from interconnected melt) of Io's mantle [7]. Plasma measurements [9] and 9+ orbits emphasizing high and low magnetic latitudes will provide definitive results. Global conductivity will need to be combined with electrical experiments in the lab to be interpreted in terms of melt fraction [15].

Near-global mapping of volcanic and tectonic landforms, hot spots, plumes, and heat flow: Global patterns relate to deep versus shallow tidal heating and the stress state of the lithosphere. The polar regions are key, and poorly observed by past missions and Earth-based telescopes. *IVO* can acquire near-global (>90%) visible mapping of Io at better than 300 m/pixel. Near-global thermal mapping at <4 km/pixel combined with improved Bond albedo and thermal inertia mapping will refine Io's present-day global heat flow. Topographic data will be provided by stereo imaging and observations of Io's bright limb. *IVO* will provide extensive monitoring of plumes and surface color changes.

Compositional constraints: The lava compositions might be ultramafic [16], which implies a large degree of mantle melting [17]. The silica content of fresh glassy lavas is best constrained by thermal emission data [18], as well as by lava eruption temperatures [19]. Mass spectra of the neutral atmosphere and plumes may help constrain Io's long-term evolution. Using the compositional constraints obtained for the surface of Io, phase equilibria experiments in the lab maybe used to place additional compositional constraints at depth.

Volcanic eruption style: How lava erupts and cools is key to understanding how Io loses heat. Very high eruption rates are inferred for past eruptions on Earth, Moon, Mercury, and Mars, but only on Io can we observe such eruptions today. Along with thermal-IR imaging well below 1 km/pixel, visible imaging will include small areas down to 2 m/pixel scale.

IVO observations could address many other science questions in addition to those driving the mission design. Future Participating Scientists and community researchers will spend decades analyzing the full dataset, which is expected to be >1000 times larger than the Io data returned by *Galileo*.

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