IO GEOPHYSICS ON THE EVE OF JUNO'S CLOSE FLYBYS.

J. T. Keane[1] & S. J. Bolton[2]. [1]Jet Propulsion Laboratory, California Institute of Technology (james.t.keane@jpl.nasa.gov); [2]Southwest Research Institute.

Introduction: Jupiter's innermost large moon, Io, is a volcanic wonderland (Fig. 1). Io is the most volcanically active world in our Solar System, with a heat flow approximately thirty times greater than Earth. This extreme level of activity is powered by tidal heating: As Io orbits Jupiter once every 42.5 hours, Jupiter's immense gravity deforms Io, generating a substantial amount of heat within its interior [e.g., 1–2]. This makes Io a priority target for understanding tidal heating and fundamental planetary processes.

The Juno spacecraft has been in orbit of the Jupiter since 2016. While Juno was designed to study the interior structure, composition, and dynamics of the gas giant, its extended mission has afforded the opportunity to have close flybys of several of the Galilean satellites. Juno is in a highly eccentric, inclined orbit (Fig. 2). Juno will have two close flybys of Io, the first in December 2023 (Juno perijove (PJ) PJ57), and the second in February 2024 (PJ58), both at an altitude of ~1,500 km. The approximate ground-tracks for these flybys are shown in Fig. 3, compared to those of the Galileo mission.

Juno's flybys represent the *last* currently planned close flybys of Io for the foreseeable future. While the NASA Europa Clipper and ESA JUICE (JUpiter ICy moons Explorer) missions are planned to explore the Jupiter system in the 2030s, neither mission is currently planned to have any close flybys of Io. These missions largely stay beyond the orbit of Europa (Fig. 2). While Juno will provide tantalizing unprecedented views of Io, much will remain unknown until a dedicated future mission to Io materializes [e.g., 3].

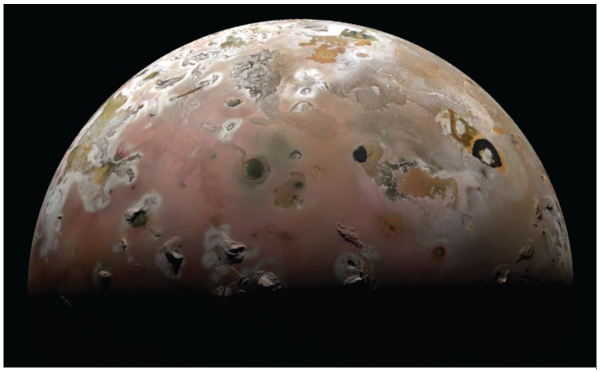


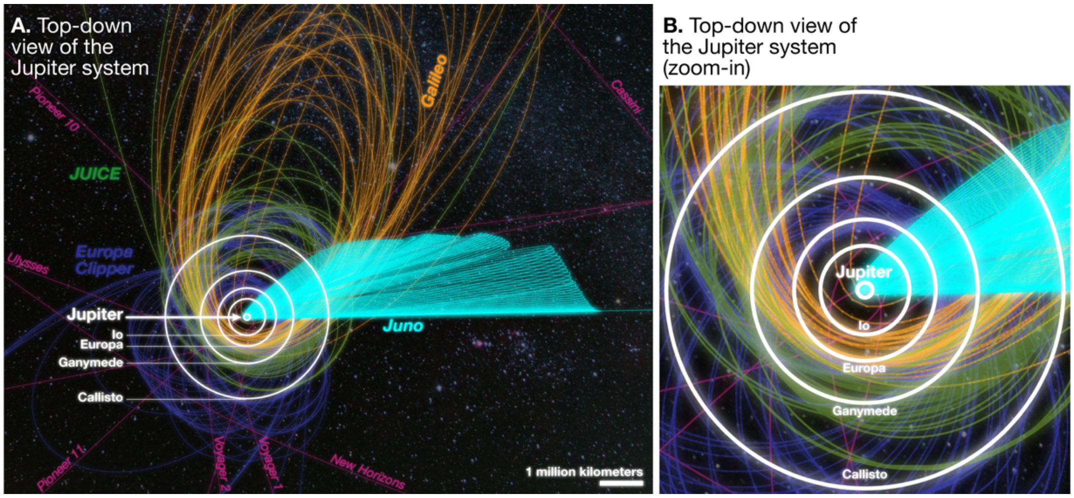
Fig. 1: *Io as seen by JunoCam on 30 December 2023 (NASA / SWRI / MSSS / Jason Perry)*

Major Questions in Io Geophysics, and how Juno may Contribute: Io is a unique world, sitting at the crossroads of many types of systems. For example, Io is a volcanically active rocky world (akin to the Earth and other terrestrial planets), but it is also a tidally heated world in a circumplanetary system (akin to other icy ocean worlds, like Europa). Io's atmosphere is dynamic, and its magnetospheric interactions with the Jupiter system may be analogous to some exoplanetary systems. In this work, we focus on major questions about Io's geology and geophysics. Despite decades of work—spanning observations, theoretical modeling, and laboratory work—many questions remain, including [e.g., 1, 3–5]:

- What is the magnitude of Io's heat flow, and is Io in thermal equilibrium (heat in = heat out)?
- Where is tidal heat dissipated within Io, and how is this reflected in surface heat flow?
- Does Io have a global subsurface magma ocean?
- What is the relationship between Io's volcanoes, mountains, and other tectono-magmatic processes?

Juno's two close flybys of Io can contribute to addressing these questions in two ways:

New geometries: Juno affords new flyby geometries compared to Galileo (Fig. 3). For gravity science, every new close flyby provides an opportunity to refine the gravity field, including constraining the tidal potential Love number, k_2, which is an important diagnostic



A. Top-down view of the Jupiter system

B. Top-down view of the Jupiter system (zoom-in)

Fig. 2: *Trajectories of past, current, and future missions to the Jupiter system. Figure by James Tuttle Keane, adapted from [3].*

of whether Io possesses a global subsurface magma ocean. The measurement of k_2 is the primary objective of Juno's Io flybys. Io's close north polar flyby (PJ57) also provides an important view of the north pole of Io. Many tidal heating models make different predictions for heat flow (and other activity) at the poles compared to the equator (Fig. 3). It is not possible to directly observe Io's poles from Earth, and previous missions including Galileo and Voyager did not acquire sufficient coverage of these regions. Preliminary analysis of the PJ57 data already has already revealed interesting details about Io's poles [e.g., 6–7].

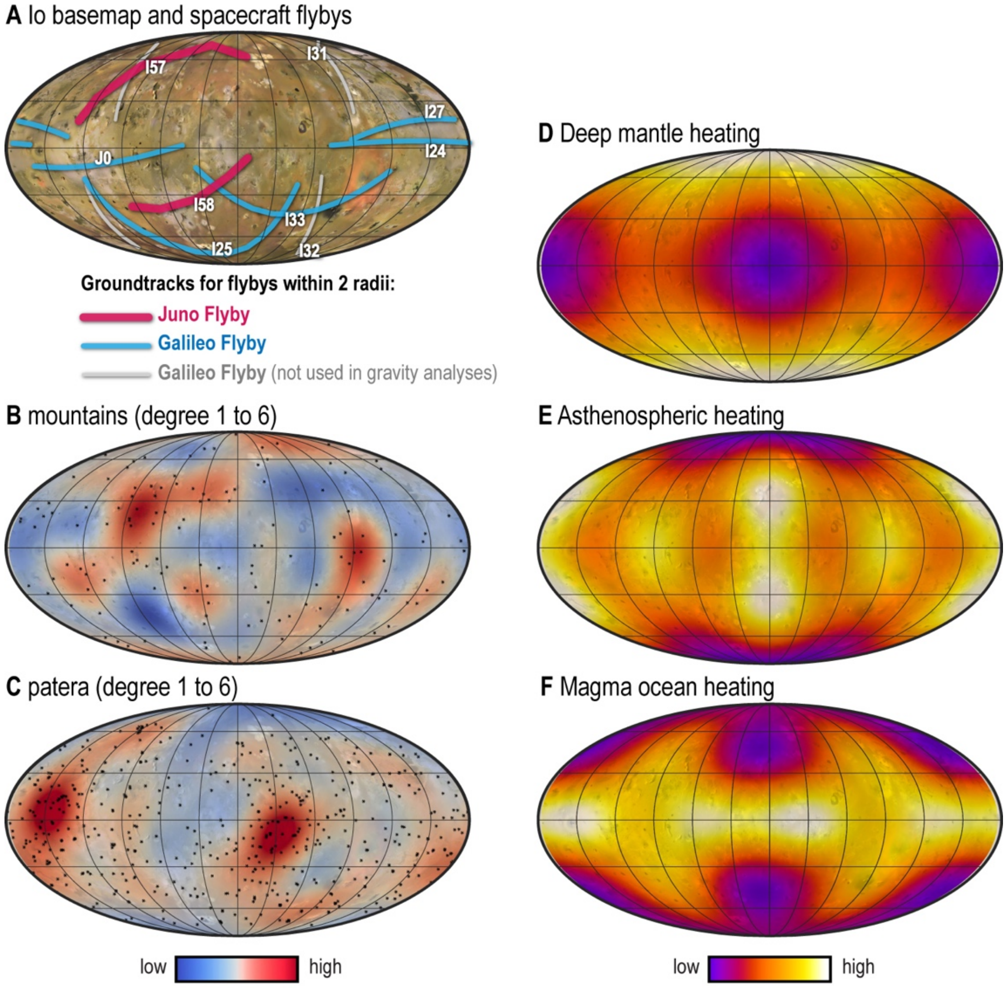
New instruments: Juno carries many new instruments that have never observed Io up close. For example, the Juno Microwave Radiometer (MWR) is providing the first in situ microwave observations of the Galilean satellites, between a frequency of 600 MHz and 22 GHz. While microwave observations are possible from the Earth (e.g., ALMA), they are intrinsically limited by resolution, viewing geometry, and complications arising from Jupiter's synchrotron emission. MWR has the potential to sound the subsurface, and may constrain thermophysical parameters like the endogenic heat flow [6]. The Juno Jovian Infrared Auroral Mapper (JIRAM) has already provided transformative views of Io in the infrared from long-range [8–9], and these close flybys will provide the opportunity to acquire high-resolution images thermal emission from volcanic features.

Next Steps: At present, the Juno team is analyzing the results from PJ57, and we eagerly anticipate the results of PJ58. We anticipate sharing new results at LPSC 2024.

Acknowledgments: J. T. Keane is supported by the Juno Participating Scientist Program.

References: [1] de Kleer et al. 2019, Tidal Heating: Lessons from Io and the Jovian System, KISS report. [2] Peale et al. 1979, Science. [3] Keane et al. 2022, Elements. [4] de Pater et al. 2021, Annu. Rev. Earth Planet. Sci. [5] Lopes et al. 2023, *Io: A new View of Jupiter's Moon*, Springer. [6] Zhang et al. 2024, LPSC. [7] Ravine et al. 2024, LPSC. [8] Zambon et al. 2022, GRL. [9] Mura et al. 2020, Icarus.

Fig. 3: *Maps of Io.* ***A****: USGS Voyager and Galileo color base-map of Io, with ground-tracks from Galileo and Juno flybys marked.* ***B–C****: the distribution of mountains and patera. Points indicate mapped features, while the color indicates the density of those features [4].* ***D–F:*** *theoretical models for the heat dissipated within Io's interior [1, 4]. Figures adapted from [4].*


A Io basemap and spacecraft flybys

B mountains (degree 1 to 6)

C patera (degree 1 to 6)

D Deep mantle heating

E Asthenospheric heating

F Magma ocean heating