IO: THE NEXT GENERATION.

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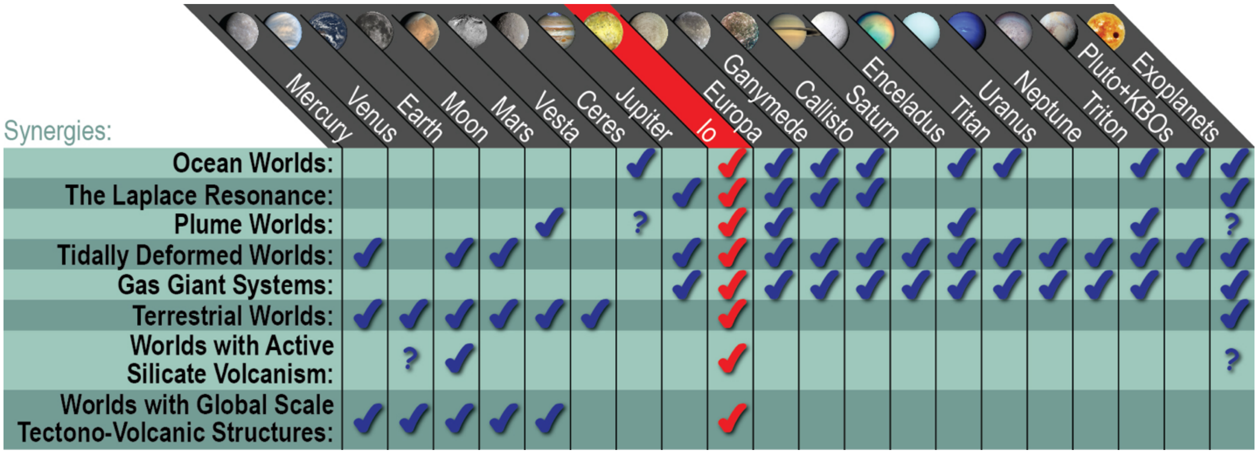
Introduction: Io, Jupiter's innermost large moon, is the most geologically active world in the solar system. Io's surface is marked by hundreds of continually erupting volcanoes, evolving exotic ices, enormous mountains, complicated tectonics, and deposits from towering volcanic plumes that pollute the Jovian system and feed its enormous magnetosphere. The nearly simultaneous theoretical prediction of magma generation by tidal heating in Io [1] and the discovery of Io's extreme activity by the Voyager spacecraft [2] established the ongoing challenge of understanding the coupling between Io's internal, magma-producing environment (geophysics, geodesy) and Io's external environment (resurfacing, atmosphere)—a challenge that remains open today. Io is the best natural laboratory for studying tidal heating and extreme volcanism. These processes are fundamental to the formation and evolution of planetary bodies and the generation of habitable environments across the cosmos—from the Hadean Earth-Moon system, to present-day ocean worlds, and exoplanets/moons [3-6]. In a sense, Io is the uninhabitable world that informs us how habitable worlds form and work.

Io exploration addresses priority questions identified in previous planetary science decadal surveys: Io is a unique solar system world—lying at the nexus of a variety of high priority, cross-cutting scientific questions in planetary science (Fig. 1). Io's high scientific potential is consistently recognized in National Research Council (NRC) planetary science decadal surveys, NASA strategic documents, and science goals developed by the planetary community [7-12].

The most recent NRC planetary science decadal survey, *Vision and Voyages for Planetary Science in the Decade 2013-2022*, ranked Io as one of the top seven destinations for the New Frontiers program. The decadal recommended Io because it is "the ideal target to study tidal dissipation and the resulting variety of volcanic and tectonic processes in action, with fundamental implications for the thermal co-evolution of the Io-Europa-Ganymede system as well as for the habitable zone around other stars." Io exploration is crucial to answering several of the "Priority Questions" outlined in the decadal survey—particularly: "How do the giant planets serve as laboratories to understand Earth, the solar system, and extrasolar planetary systems?" and "How have the myriad chemical and physical processes that shaped the solar system operated, interacted, and evolved over time?" Io's fundamental scientific importance was reaffirmed in both the NRC midterm review, *Vision into Voyages for Planetary Science in the Decade 2013-2022: A Midterm Review* (2018), and the NRC Committee on Astrobiology and Planetary Science (CAPS) report, *Getting Ready for the Next Planetary Science Decadal Survey*.

Io exploration is endorsed by multiple different planetary science communities. The Outer Planets Assessment Group (OPAG) *Roadmap to Ocean Worlds* [13] noted that Io is a critical science destination for understanding its icy compatriots (e.g., Europa, Enceladus, Titan). The NRC heliophysics decadal survey, *Solar and Space Physics: A Science for a Technological Society* (2013), identified Io and the Jupiter system as a prime destination for "critically



Synergies:	Mercury	Venus	Earth	Moon	Mars	Vesta	Ceres	Jupiter	Io	Europa	Ganymede	Callisto	Saturn	Enceladus	Titan	Uranus	Neptune	Triton	Pluto+KBOs	Exoplanets
Ocean Worlds:							✓		✓	✓	✓	✓		✓	✓			✓	✓	✓
The Laplace Resonance:								✓	✓	✓	✓	✓								✓
Plume Worlds:					✓		?		✓	✓				✓				✓		?
Tidally Deformed Worlds:	✓		✓	✓				✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Gas Giant Systems:								✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
Terrestrial Worlds:	✓	✓	✓	✓	✓	✓			✓											✓
Worlds with Active Silicate Volcanism:		?	✓						✓											?
Worlds with Global Scale Tectono-Volcanic Structures:	✓	✓	✓	✓	✓				✓											

Figure 1: *Io is a synergistic nexus in the solar system. Exploration of Io is relevant to our understanding of rocky and icy worlds in our solar system and beyond. IoTNG will address key cross-cutting themes in planetary science.*

advancing the physical understanding of magnetospheres and their coupling to ionospheres and thermospheres." The exoplanet community is also critically invested in understanding Io, as it is an analog for an entire class of scientifically critical, tidally heated exoplanets and exomoons [14-15].

Now is the best time to reexamine Io exploration: Both the NRC midterm review and CAPS predecadal report specifically call out the need to reevaluate the scientific case and technological feasibility of an Io mission. The only publicly available Io mission concept study is the Io Observer study performed for the previous decadal survey [16]. While compelling at the time, this study is now outdated.

In the last decade, significant advances have been made in our understanding of Io that have changed the paradigm for Io exploration. New and innovative techniques have enabled extremely high-resolution ground-based imaging of individual bright Ionian volcanoes [17-18]. Reanalysis of Galileo magnetometer data revealed the presence of a global subsurface magma ocean on Io [19], although that result is debated [20-21]. Studies of Voyager, Galileo, and telescopic data have characterized aspects of the spatial distribution of Io's volcanism [22-27]. New Horizons provided an exciting high-resolution snapshot of Io on its way to Pluto [28], and Juno has revealed new aspects of Io's previously unexplored polar regions (although at limited wavelengths and resolutions). Radar measurements have placed new constraints on the obliquity of the Galilean satellites [29]. Precise astrometric measurements have provided key constraints on the orbital migration of Galilean and saturnian satellites [30-32]. Theoretical models have dramatically improved, and are coming closer to explaining tidal dissipation in solid bodies [33], subsurface oceans [34] and gas giants [35]. These advances necessitate the development of new mission architectures that can address the new priorities and scientific hypotheses of the community.

The exoplanet revolution also motivates Io exploration. Exoplanet searches have now detected thousands of worlds. One intriguing example is TRAPPIST-1: a system with seven, Earth-sized terrestrial planets in orbital resonances analogous to the Io-Europa-Ganymede system. Tidal heating may drive some of these worlds to be habitable, and turn others into Io-like volcanic hellscapes [36]. Forthcoming surveys (TESS, CHEOPS) will discover these worlds in droves, and shift exoplanet research from "discovery" to "characterization." Telescopes like GMT, TMT, and JWST, will be capable of detecting and monitoring volcanic activity on these worlds—albeit with sparse, unresolved, and photon-limited data. We may also soon discover exomoons even more explicitly analogous to Io. Therefore, now is the time to address critical knowledge gaps about the fundamental processes of tidal heating and extreme volcanism in order to capitalize on the forthcoming exoplanet boon. Io has the potential to be the Rosetta Stone of planetary heating, tides, and volcanism.

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