Ionian Plumes: High-Value Targets for a Sample Return Mission. A. O. Adeloye[1], R. C. Ogliore[2], A. E. Hofmann[3], M. Choukroun[3], H. A. Ishii[4], J. M. Eiler[5], A. Freeman[3], R. Karimi[3], L. Shiraishi[3], J. C. Aponte[6], S. Tachibana[10], F. L. H. Tissot[5], L. Saper[3], T. E. Yap[5], M. E. Brown[5], D. L Buczkowski[7], V. Forero[8], P. Gerakines[6], J. M. Jackson[5], Y. Liu[3], K. J. Meech[4], A. Meshoulam[5], A. Mojarro[6], M. Neveu[6,9], C. A. Raymond[3], H. Yabuta[8], M. Zolensky[11], [1]The University of Texas at Austin, [2]Washington University in St. Louis, [3]Jet Propulsion Laboratory, California Institute of Technology, [4]University of Hawaiʻi at Manoa, [5]California Institute of Technology, [6]NASA Goddard Space Flight Center, [7]Johns Hopkins University Applied Physics Laboratory, [8]Hiroshima University, [9]University of Maryland, College Park, [10]University of Tokyo, [11]NASA/Johnson Space Center (adeloye@utexas.edu)

Introduction: Io, the most volcanically active body in the Solar System, features hundreds of active volcanoes that produce towering plumes exceeding 100 km in height and width. These plumes contain sulfur dioxide (SO_2), various sulfur species, and pyroclastic dust grains. Voyager 1's 1979 flyby revealed a startlingly dynamic world, replacing expectations of a cratered, ancient surface with images of smooth plains, towering mountains, volcanic calderas, and extensive lava flows and plumes of gas and dust grains [1]. This discovery challenged existing assumptions about planetary geology and positioned Io as a critical target for understanding the effects of intense internal processes.

Subsequent spacecraft missions, including Galileo, New Horizons, and Juno, and ground-based observations, have deepened our understanding of Io's geology, atmosphere, and interactions within the Jovian system [2–7]. However, many fundamental questions remain unanswered, particularly regarding Io's formation, volatile history, and internal structure. These mysteries make Io a prime candidate for a sample return mission to address key scientific questions. Io sample return was recently studied as part of the Keck Institute for Space Studies workshop "Sample Return from All Across the Solar System".

Why Io? A Unique Opportunity for Planetary Science: Io's dynamic and extreme environment offers a unique opportunity to address fundamental questions about planetary formation and evolution. Current models suggest Io formed in Jupiter's circumplanetary disk, likely under high-temperature conditions as the solar nebula dissipated [8–11]. However, critical uncertainties persist, including Io's initial volatile inventory, the extent of core and mantle differentiation, and the timescales of its accretion and orbital evolution [11–22].

Returning samples from Io would allow for direct analysis of its bulk composition and isotopic signatures, shedding light on its volatile history, including whether it accreted water ice and later lost it through hydrodynamic escape or tidal heating [18]. Isotopic measurements of sulfur and oxygen could reveal the oxidation state of Io's mantle and the processes driving its volcanic activity [19–20]. Such data would also refine models of Io's migration history and provide insights into its early tidal evolution within a dissipative nebula [21–22]. By connecting Io's evolution to the broader processes of giant planet formation, these findings would have implications for the assembly of the entire Jovian system and beyond. A returned Io sample can address the following science questions:

- What are the different styles of volcanism, plume types, source compositions, plume-surface interactions, and core-mantle interactions?
- What is the sulfur chemistry on Io's surface and how do different sulfur compounds form?
- Do Io plumes erupt mantle xenoliths? If so, how do they differ from the magma?
- How is surface material on Io affected by the intense radiation environment?
- How is the crust recycled during long periods of volcanic activity?
- Is the effect of billions of years of volatile loss recorded in the isotopic composition of moderately volatile elements? Do lab analyses of Io material show the extreme isotope anomalies in S and Cl measured in ground-based observations of Io's atmosphere [23]?
- Do Io plumes contain hydrogen at trace levels? If so, what is their D/H ratio?
- Given Io's position in the Jovian system, how does Io's isotopic composition reflect the extent to which Jupiter kept the NC and CC reservoirs [25] separated?
- What is the provenance of Io's building blocks? Was Io built from a combination of known meteorite types?
- How do Io's building blocks and volatile loss constrain the timing of its capture in its Laplace resonance with Europa and Ganymede?
- Did Io accrete icy like Europa?
- When did Io's core form?
- How does the Io plasma torus form?
- How and when did the silicate portion of Io differentiate? Are there multiple

geochemical reservoirs in the silicate portion of Io?
- Is there a "late veneer" on Io and other satellites in the outer Solar System?
- How do Io's differentiation age and building blocks constrain the formation of the Jovian system and the dispersal of the solar nebula?

Most of these questions can be addressed with high-precision isotope measurements of a returned Io sample. For example, the formation time of Io's core and possible interaction with the mantle can be probed with the Hf-W system [24]. Io's building blocks in comparison with the NC and CC meteorites can be constrained with high-precision isotope measurements of Cr, O, and other systems [25]. If the silicate portion of Io is well-mixed and Io formed from chondritic-like neodymium, the Nd isotope measured in a modern Io sample would be similar to the chondritic uniform reservoir [26].

A Practical Mission Design: Hypervelocity Plume Sampling: Given the high Δv (~9.0 km/s) required to access and depart from the Jupiter system, a hypervelocity plume-sampling approach, similar to the Stardust mission, offers a practical solution for collecting material from Io [27]. By flying through Io's plumes at hypervelocity (~6.0 km/s), a spacecraft could collect volcanic material without needing to land on its surface and be exposed to extreme levels of radiation [27]. The mission duration is estimated to be approximately 9.4 years, based on projections leveraging advancements in propulsion technologies currently under development [28].

Broader Implications for Planetary Science: Understanding Io's composition and evolution would have profound implications for planetary science. By constraining conditions in Jupiter's circumplanetary disk and the timing of satellite formation, data from an Io sample return mission could refine models of giant planet formation and migration. The detailed analysis of Io's volcanic processes, isotopic anomalies, and magmatic diversity would provide critical comparative data for studying other planetary bodies and inform broader questions about Solar System evolution. Io serves as an analog to important worlds inaccessible in time and space. Tidal heating is an important process, and likely rather common in exoplanets and their satellites [29]. As a possible heat-piping planet, Io serves as a link to the Archean Earth as well as the early years of the other terrestrial planets [30].

Conclusion: A sample return mission to Io offers an extraordinary opportunity to address fundamental questions about planetary volcanism, satellite formation, and the evolution of the Jovian system. By leveraging plume-sampling techniques and state-of-the-art laboratory analyses, such a mission promises to extend the legacy of transformative discoveries achieved through past sample return missions. Io's dynamic nature makes it a cornerstone for the next generation of planetary science, with the potential to unravel the mysteries of our Solar System's most volcanically active world.

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