Io Sample Return: A Critical Missing Link in Planetary Science

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Introduction: Volcanic plumes on Jupiter's moon Io launch pyroclastic debris more than 10 km above its surface, offering an opportunity for sample return from a world about the size our Moon without the cost and complexity of a landed mission [1]. With a few hundred milligrams of this material, high-precision lab isotope and element measurements of "bulk silicate Io" can tell us about Io's origin and early evolution (information that is erased from its young surface) [2]. Though Io, with its extreme tidally-driven volcanism, may seem like a Solar System oddball, it is actually a critical missing link in our understanding of the Solar System's origins, the formation and early evolution of planets, habitability in tidally heated worlds, and exoplanets.

Link between Noncarbonaceous and Carbonaceous Solar System Reservoirs: The NC and CC reservoirs are proposed to have been kept separate by an early forming Jupiter [3]. High-precision analyses of Cr, Ti, and other isotope systems can test models of these hypothetical Solar System reservoirs. If carbonaceous chondrites formed in the outer Solar System and were the building blocks of the giant planets, the isotopic composition of the Io sample could be expressed as a linear combination of known carbonaceous chondrites. An alternative, and more likely, hypothesis is that our understanding of the Solar System's building blocks is incomplete because our collections are limited to bodies currently on Earth-crossing orbits. In this scenario, the composition of the Io sample could not be expressed in terms of known meteorite types.

Link between the formation and adolescence of the terrestrial planets: Io may be a window back to the early years of Earth and the other terrestrial planets. In the heat-pipe model, Io is representative of the terrestrial planets after the magma ocean phase and before the stagnant lid [4]. High-precision measurements of Fe, Mg, and Si can give insights into high-temperature volatile depletion in a heat-piping Io. Additionally, Io may erupt very high temperature lavas that are similar to komatiites from the Archean period of the ancient Earth [5]. An understanding of the similarity of Io's lavas to Earth's lavas is only possible with high-sensitivity measurements of major, minor, and trace elements of Io's lava in Earth labs.

Link between planet formation times in the inner and outer Solar System: The formation time of Io's core, with ~0.1 Myr precision, can be calculated using the Hf-W system on a returned Io sample. This age can be compared to the formation ages of the Earth, Moon, Mars, and Vesta [6]. Once Io's formation age is known, we can use accretion models to better understand the formation times of the Jovian system and other bodies in the outer Solar System. The abundance of W in the Io sample will likely be low, ~200 ppbw, but current analytical techniques are so sensitive that we only need nanograms of W to make the measurement [7] (corresponding to less than 5% of the anticipated collected sample mass).

Link between icy builidng blocks and habitability: Io's neighbor Europa is a possibly habitable ocean world. Io may have formed icy, like Europa, and subsequently lost its volatiles. A signature of a volatile-rich origin for Io would be recorded in mass-dependent fractionation of volatile and moderately volatile elements in a collected Io sample ($^{34}S/^{32}S$ has been measured telescopically to be high in Io [8]). Currently, Io may be delivering elements necessary for life to Europa's surface through its volcanic eruptions [9]. High-sensitivity analyses of Io's volcanic material will yield the abundances and types of matter that may be deposited on Europa's surface, where it may eventually be incorporated into its subsurface ocean. Additionally, Ionian volcanic emissions can become ionized and interact with Jupiter's magnetosphere to create the Io plasma torus. This irradiation environment is inhospitable to life, unless it is shielded (e.g., by Europa's ice shell) . It is possible to understand the formation mechanism of the Io plasma torus through combined analyses of returned ions, dust, and gas from Io.

Link between the Solar System and exoplanetary systems: Ganymede, Europa, and Io are locked in a 4:2:1 orbital resonance, similar to some exoplanetary systems [10]. Tidal heating can be a major cause of geologic evolution in exoplanets, as it is on Io. A possible exo-Io, detected by a Na cloud, has been discovered around a hot Saturn orbiting the Sun-like star WASP-49 [11]. Understanding Io's building blocks, formation age, and volatile loss will help us understand how tidally heated exoplanets elsewhere formed and evolved.

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