THE SCIENCE CASE FOR IO SAMPLE RETURN. R. C. Ogliore[1], R. M. C. Lopes[2], A. E. Hofmann[2], N. J. Turner[2], S. J. Bolton[4], K. R. de Kleer[5], W. A. Hoey[2], J. Kargel[3], J. T. Keane[2], Y. Liu[2], W. B. McKinnon[1], K. L. Mitchell[2], A. V. Oza[2], R. Parai[1], W. D. Smythe[2], Z. Váci[1], L. Vanderkluysen[6], D. A. Williams[7], R. Wright[8], M. Yu. Zolotov[7]. [1]Washington University in St. Louis, [2]Jet Propulsion Laboratory, California Institute of Technology, [3]Planetary Science Institute, [4]Southwest Research Institute, [5]California Institute of Technology, [6]Drexel University, [7]Arizona State University, [8]University of Hawaii at Manoa.

Introduction: Sample return has proven effective at establishing "ground truth" of planetary bodies, usually upending our expectations. For example, the Stardust mission returned high-temperature igneous rocks from comet Wild 2, which was thought to be dominated by primordial interstellar dust kept cold since the Solar System's formation [1], Genesis showed that the Sun's oxygen isotopes were significantly lighter than the rest of the Solar System [2], and returned lunar samples revealed that Earth's supposedly bone-dry Moon contains significant water [3]. The benefits of sample return are increased precision, sensitivity, and spatial resolution, as well as the flexibility in analysis flow (i.e. results of one analysis technique dictate the next) when the sample defies expectations. A returned sample can wait for analytical techniques (and science return) to improve over decades, as has been shown with the Apollo and Luna samples.

Jupiter's volcanic moon Io contains a record of extreme planetary processes and the building blocks of Jupiter's circumplanetary disk. Tidal heating, volcanism, resurfacing, volatile loss, and radiation are all extreme on Io and affect other planets and exoplanets to varying degrees (e.g. [4]). Lab analyses of Io samples could address important questions related to the origin of the Solar and Jovian systems, the evolution of Io into what it is today, and the processes that characterize Io's current volcanic activity.

Accessibility of an Io Sample: Volcanic plumes on Io have been observed during every spacecraft encounter: Voyagers 1 and 2 (e.g. [5]), Galileo (e.g. [6]), Cassini [7], New Horizons [8], and Juno. At higher altitudes, these plumes are largely composed of SO_2 gas and condensing SO_2 and S_n frost. At altitudes below ~50 km, the optically opaque plume core likely contains pyroclastic grains and recycled surface deposits up to hundreds of micrometers in size [9,10]. At least a fraction of pyroclastic grains are likely samples of Io's magma [11]. A spacecraft flying through a plume could collect pyroclastic grains and condensed materials together with gases. Ions from the Io plasma torus can be collected as well.

Collecting Plume Dust, Gas, and Ions: It is energetically expensive to enter and escape from the Jupiter system, so it is much more feasible to sample Io's plumes at hypervelocity like the Stardust mission (~6 km/s) rather than the near-zero encounter speed of e.g. OSIRIS-REx. Solids returned by Stardust captured in aerogel were remarkably well-preserved, even fine-grained material [12]. Impacts of Wild 2 dust into Al foil also contained residue that could be analyzed, including moderately volatile sulfides [13]. Io's silicate magmatic pyroclastics will have higher material strength than Wild 2 dust, and so it is likely that they will survive capture in aerogel, and residues will survive in a metal substrate (either a plate or porous nanofibers).

Primitive bodies like comet Wild 2, Ryugu, and Bennu are "cosmic sediments" containing grains formed in very different environments. These samples are more usefully analyzed on a grain-by-grain basis using in situ techniques like TEM and SIMS, but samples from a differentiated body like Io have more meaningful bulk properties. Analyses of many Io plume dust grains simultaneously will allow for precise measurements of rare elements and isotopes. Collection into a pure-metal substrate, like those flown on Genesis, would allow for "bulk" analyses of Io dust. In situ lab analyses of individual grains will help constrain the magmatic diversity of Io and the magmatic evolution of the sampled volcano.

A Stardust-sized collector (0.1 m^2) consisting of both aerogel and pure metal substrates would collect ~100 mg of material during a plume flythrough at 10-km altitude [10] (assuming a dust/gas mass ratio of 0.5). Recent ICP-MS analyses of analog hypervelocity impacts of olivine into Si, at the expected density for an Io sample collection, show that bulk compositions can be accurately measured this way [14]. A BaF_2 substrate in the collector, transparent to the CO_2 laser used in laser fluorination analyses [15], can be used to make a precise triple O isotopic measurement of Io solids. Collection of gas could be done through a simple tank-valve system, similar to that proposed for the SCIM concept to sample the Martian atmosphere [16], and the system used recently to collect stratospheric gases by high-altitude balloon [17]. Gas vessels and some solid collecting media can be outgassed by heating in space before the collection event, minimizing the effects of contamination. The expected gas collected (through a 1 cm^2 aperture) is ~10^{18} molecules [10], which is sufficient for isotope analyses of even rare noble gases. Magmatic gases could also be analyzed in gas inclusions in sampled grains. Ions from the plasma torus (mostly S and O) with energies of hundreds of eV will implant into a C substrate with peak depths of 1-2 nm and larger surface density than the same solar wind ions collected in the Genesis BC array (assuming six Io encounters) [18,19]. These ions can be measured using SIMS techniques developed for analyzing the Genesis samples [18].

The following are three high-priority science questions that can be addressed by a returned sample of dust, gas, and ions from an Io plume.

What were the building blocks of Jupiter and its circumplanetary disk? High precision analyses of solid samples of asteroids, the Moon, Earth, and Mars show a division into two compositional reservoirs [20]. Non-carbonaceous (NC) and carbonaceous chondrite (CC) bodies are proposed to have formed with different nucleosynthetic anomalies and kept separated by the formation of Jupiter [20]. Io formed from the same primordial solids as Jupiter and its (mass-independent) nucleosynthetic anomalies should be intact despite thorough recycling of its solids. High-precision isotope analyses of O, Cr, Ti, Ni, Mo, and other elements will allow us to constrain the origins of Jupiter-system solids in relation to these reservoirs. For example, if Io solids have similar compositions as the NC group, it is likely that injection of r-process material occurred preferentially in the outer Solar System after Jupiter separated the two reservoirs. On the other hand, the volatile content of the other Galilean satellites implies a strong input from CC or more distant reservoirs.

What was Io's initial volatile inventory, and how has its material evolved since then? Io may have formed with an early surface liquid water ocean that was subsequently lost by vapor escape [21]. Any remaining H would show large enrichments in deuterium, which can be measured in the returned gas sample or in pyroclastic glasses [e.g. 22]. If Io accreted relatively far from Jupiter and subsequently migrated, it may have formed with as much ice as Ganymede has today [23]. Traces of C-, H-, or N-bearing volatiles may still be present in the returned samples. Since Io's formation, material has been volcanically recycled between its mantle and crust. Some material escaped to space, which contributes to the Io plasma torus [24]. These processes fractionate the isotopes of S (and other elements; their relative contributions can be constrained by S isotope measurements (‰ precision) of the returned gas, dust, and ions [e.g., 25].

What are the compositions of Io's silicate magma and plume gases? The composition of Io's magmas (basaltic vs. ultramafic; alkaline vs. non-alkaline) is one of the outstanding questions related to Io volcanism. The rapidly quenched pyroclastics are high fidelity recorders of the lava composition [e.g., 26]. Remote spectroscopic observations can be hampered by non-silicate surface condensates (SO_2, S_n), but a magmatic sample would allow for precise determination of major and trace elements, and isotopes. This will constrain conditions in magma source regions, and the pre-eruptive evolution and redox state of the magma. A returned sample of plume gases would enable a detailed investigation of Io's interior volatiles, with bearing on volatile origins, loss, recycling, and mantle mixing. Plume gases could inform the temperature, type, and redox state of magma [29,30]. Of the candidate gases in the plumes, only SO_2, SO, S_2 and S have been confirmed [28] (as well as NaCl and KCl in the atmosphere [e.g., 31]). Other gases (e.g., CO_2, CO, H_2O, H_2S, H_2) are not excluded. The possibility of very low abundances of other gases in the plumes is what makes a sample return mission so critical – it is necessary to leverage the high sensitivity, mass discrimination and precision achievable in terrestrial labs to answer questions about the origins and fate of Io's volatiles.

Na and K have been identified in the Io torus and at several gas giant exoplanet systems in transmission spectroscopy, suggestive of extrasolar Ios [32]. The search for volcanic exo-Ios has been encouraged by the recent Planetary Science and Astrobiology Decadal Survey 2023-2032 [33], where a precise determination of Io's magmatic material would help quantify remote spectroscopic observations.

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