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Evidence of long-lived volcanism on Jupiter's moon Io from sulfur and chlorine isotopes

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Jupiter's moon Io hosts extensive volcanism driven by tidal heating due to its Laplace resonance with Europa and Ganymede. Io's rapid resurfacing erases any surface signatures of its geological history, but the isotopic composition of its volatile inventory reflects its outgassing and atmospheric mass loss history, providing an alternative avenue for exploring its evolution.

We used millimeter observations of Io's atmosphere from the Atacama Large (sub-)Millimeter Array (ALMA) to measure sulfur isotopes in gaseous SO_2 and SO, and chlorine isotopes in gaseous NaCl and KCl. We find $^{34}S/^{32}S=0.0595\pm0.0038$ ($\delta^{34}S=+347\pm86$‰), which is highly enriched compared to average Solar System values and indicates that Io has lost 94 to 99% of its available sulfur. Our measurement of $^{37}Cl/^{35}Cl=0.403\pm0.028$ ($\delta^{37}Cl=+263\pm88$‰) shows chlorine is similarly enriched.

We constructed a numerical model for Io's sulfur cycle that describes the rates of sulfur exchange between reservoirs and the associated isotopic fractionations. The primary isotopic fractionation mechanism for sulfur is the gravitational stratification of SO_2 in the upper atmosphere, leading to decreasing $^{34}S/^{32}S$ with increasing altitude; mass loss from the top of the atmosphere leads to higher $^{34}S/^{32}S$ in the residue. Efficient recycling of the atmospheric escape residue into the interior is required to explain the magnitude of $^{34}S/^{32}S$ enrichment; we propose that this recycling occurs by SO_2 surface frost burial as well as SO_2 reactions with crustal rocks, which founder into the mantle and/or mix with mantle-derived magmas as they ascend.

Our sulfur measurement and modeling indicate that Io has been volcanically active at a rate comparable to (or even greater than) the present day for most or all of its history, consistent with an ancient onset of the Laplace resonance.