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Elemental and isotopic fractionation as fossils of water escape from Venus

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We develop a new model of diffusively modulated hydrodynamic escape to predict oxygen isotopic fractionations caused by the loss of water from Venus. The chief technical advance over previous work is including CO2 as a major species. We find that ordinary (δ18O) and mass-independent (Δ17O) fractionations depend mostly on the extent of lithospheric buffering and the ferocity of EUV heating when escape took place, and relatively less on the size of the lost ocean(s). It is likely that Δ17O evolved significantly from its birth state, not only in the atmosphere but also in the silicates of the crust and upper mantle. Escape undermines Δ17O as a tracer of planetary genetics, because any measurement of Δ17O that differs from Earth can be attributed to escape rather than to genetics. Taken together, δ18O and Δ17O are most useful for determining when escape took place and the extent of oxygen exchange with the lithosphere. We also address Ne, Ar, nitrogen, and D/H as passive tracers of water escape. Neon and argon systematics are consistent with minimal hydrodynamic escape if an Ar-rich source, possibly derived from comets, is added. We also explore a novel class of models in which Ne and Ar of Venus, Earth, and Mars are evolved from a common source material subject to different vigors of hydrodynamic escape, least extreme for Earth and most extreme for Mars. These kinds of models require that Venus was always rather dry (<10% of an Earth ocean) and its water lost very early (before <100 Myrs). The two styles of escape – minimal or extreme – should be readily distinguished by an unambiguous measurement of the Ar/Kr ratio. In either case, nitrogen fractionation is closely linked to Ne escape. Finally, we find that computed D/H enrichments are of order 100 for a very wide range of model parameters.

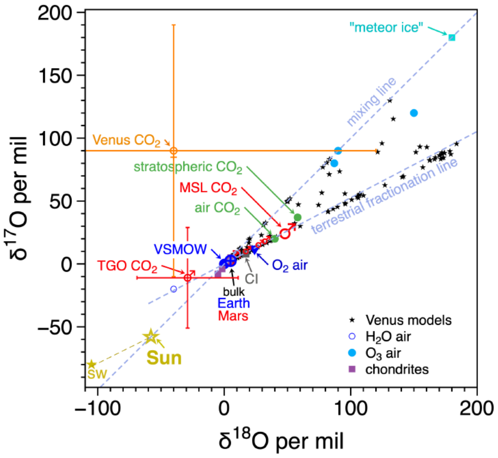

Figure 18: *The constellation of our models plotted on the oxygen isotopes in the inner solar system. Our models fall in the wedge between the mixing line (slope one) and a mass-dependent fractionation line with slope* $\lambda \approx 0.49$*, close to the* $\lambda = 0.501$ *expected for a purely gravitational process (Dauphas and Schauble, 2016). Very large values of* $\delta^{17}O$ *and* $\delta^{18}O$ *correspond to minimal interaction with Venus's lithosphere (either* $L = 1$ *km or*

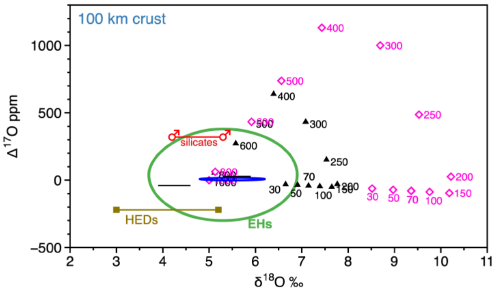

Figure 16: *Oxygen fractionations caused by the loss of an ocean of water when isotopic exchange is limited to the top 100 km of the mantle, picked as proxy for a stagnant lid (O'Rourke and Korenaga, 2015) or a weakly interacting magma ocean (Salvador and Samuel, 2023). Diluting the signature of escape in 100 km of rock nevertheless leaves isotopic signatures in the atmosphere and crust that are uninterpretable as provenance.*