Cold Moon formation revealed by chromium isotopes

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Terrestrial and lunar rocks share chemical and isotopic similarities that likely result from vigorous mixing in the aftermath of the giant impact [1, 2]. The depletion of volatile elements in the Moon with respect to the Earth is a notable exception.

The heavy isotope enrichments of Zn, K, Rb and Ga in the Moon compared with the Earth has been taken to imply that evaporation was the driving mechanism for their depletion [3-6]. However, because these elements are all more reduced in the gas than in the melt, both kinetic- and equilibrium evaporation would cause heavy isotope enrichment in the residue. It has therefore been impossible to evaluate whether equilibrium prevailed between the liquid and gas, and, if so, at what conditions (temperature, pressure and fO_2) this occurred. By contrast, chromium has thermodynamically stable gas species in which it is in a higher oxidation state than in the melt, such that equilibrium isotope fractionation between liquid and vapour should uniquely result in an isotopically light Moon.

Here, we present new high-precision Cr isotope measurements in primitive terrestrial (komatiites) and lunar rocks (mare basalts, Mg Suite cumulates) that show that the Moon is enriched in the lighter isotopes of Cr compared to the Earth's mantle by 50 ppm per atomic mass unit. This observation cannot be accounted for by core formation and instead implies that Cr was evaporated from the Moon at oxygen fugacities higher than that required to form iron metal, thereby stabilising the oxidised CrO_2 gas species.

These observations require temperatures of 1200 (+1100/-300) K, far below peak temperatures reached during a giant impact.

[1] Zhang et al. (2012), *Nature Geo.* **5**, 251-5. [2] Young et al. (2016), *Science*, **351**, 493-6. [3] Paniello et al. (2012), *Nature*, **490**, 376-9. [4] Wang & Jacobsen (2016), *Nature*, **538**, 487-490. [5] Kato & Moynier (2017) *Sci. Adv.* **3**, e1700571. [6] Pringle & Moynier (2017) *Earth Planet. Sci. Lett.* **473**, 62-70.