OXYGEN ISOTOPE EVIDENCE FOR A HIGH-ENERGY MOON-FORMING GIANT IMPACT AND EARLY DELIVERY OF EARTH'S WATER.

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Introduction: The Earth-Moon system likely formed in the aftermath of a high-energy collision between two planetary objects [1]. Debate continues about the relative masses of these bodies, the impact energy involved, and the extent of mixing and homogenization [2-5]. To investigate the early evolution of the Earth-Moon system, we have undertaken a high-precision oxygen isotope study, involving an extensive suite of lunar and terrestrial samples [6].

Methods and samples: Lunar whole-rock samples (n = 17) covering all the main lithological units, from all six Apollo landings, were analysed, as well as lunar mineral separates (n = 14). Terrestrial mafic rocks comprised basalts (n = 20) and a mantle xenolith. The terrestrial sample set also included our previously published olivine data [7].

Results: Lunar whole-rocks have relatively homogeneous oxygen isotope compositions, with $\delta^{18}O$ values that range from 5.64 ± 0.02‰ (2 SD) to 6.19 ± 0.02‰ (2 SD) and $\Delta^{17}O$ values from 2 to 20 ppm. In comparison, terrestrial whole-rocks show a wider spread in $\delta^{18}O$, ranging from 5.03 ± 0.12‰ (2 SD) to 6.27 ± 0.15‰ (2 SD), and have $\Delta^{17}O$ values from -4 to 15 ppm. However, the mean $\delta^{18}O$ values of the lunar and terrestrial whole-rocks are close, 5.92 ± 0.28‰ (2 SD) and 5.79 ± 0.69‰ (2 SD) respectively. There is a 3 ppm difference between the average $\Delta^{17}O$ value of lunar and terrestrial samples, with the full suite of lunar whole-rocks and mineral separates (n = 31) having a mean $\Delta^{17}O$ composition of 10 ± 2 ppm (2 SEM), compared to 7 ± 2 ppm (2 SEM) for all terrestrial samples and mineral separates (n = 37). When terrestrial basalts ($\Delta^{17}O$ = 6 ± 2 ppm (2 SEM) (n = 20)), are compared to lunar whole-rocks this difference increases to 4 ppm. Statistical analysis (t tests and bootstrap analysis with 10^6 replications) indicates that these 3 to 4 ppm differences are significant at a 95% level of confidence [6].

An aubritic composition for Theia? The aubrites provide the closest match to the hypothesized reduced impactor of [8], being virtually FeO-free [6]. Aubrites are also isotopically and compositionally close to enstatite chondrites, from which the Earth was predominately accreted [9]. High-precision oxygen isotope data for aubrites have an oxygen isotopic composition ($\Delta^{17}O$ = 28 ± 3 ppm (2 SEM)) close to, but fully resolvable from, that of the Earth and Moon [6,10]. Using the parameters of the canonical impact model [1] and taking the isotopic composition of the impactor to be that of the aubrites, we have calculated the proportions of impactor and target material in the Earth and Moon required to account for the oxygen isotopic differences observed in our data. This analysis indicates that the 3 to 4 ppm $\Delta^{17}O$ difference between terrestrial and lunar rocks is not consistent with an aubritic impactor, unless some form of post-impact equilibration also took place. In the absence of such an event, the impactor would have needed to be much closer in oxygen isotope composition to the proto-Earth than aubrites. While not impossible, we would argue that this is unlikely. Our results are consistent with high energy impact models [2, 3], which allow a limited differential impactor component in the Moon compared to Earth. However, if near-total mantle equilibration took place in the aftermath of the giant impact [5], then the 3 to 4 ppm Earth-Moon $\Delta^{17}O$ difference requires a post-impact explanation.

Relative timing of water delivery to Earth: Highly siderophile element (HSE) data indicate that following the giant impact, the Earth and Moon received an input of chondritic material [11]. However, the amounts accreted by the two bodies were very different, being ~ 0.5 wt. % of the terrestrial mass and ~ 0.02 wt. % of the lunar mass, respectively [11]. The 3 to 4 ppm Earth-Moon $\Delta^{17}O$ difference indicates that post–giant impact additions were likely to be dry types, in particular enstatite chondrites [6]. A small fraction of hydrated material is permissible and could have contributed between 5 and 30% of Earth's water [6]. Consequently, the data indicate that the bulk of Earth's water was accreted before the giant impact and not later, as often proposed e.g. [12]. The possibility that oceans were present on Earth at the time of the giant impact [13] is consistent with the results of this study.

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