OXYGEN ISOTOPIC EVIDENCE FOR VIGOROUS MIXING DURING THE MOON-FORMING GIANT IMPACT. Edward D. Young[1], Issaku E. Kohl[1], Paul H. Warren[1], David C. Rubie[2], Seth A. Jacobson[2,3], and Alessandro Morbidelli[3], [1]Department of Earth, Planetary, and Space Sciences, University of California Los Angeles, Los Angeles, CA, USA,[2]Bayerisches Geoinstitut, University of Bayreuth, D-95490 Bayreuth, Germany,[3]Laboratoire Lagrange, Universite' de Nice - Sophia Antipolis, Observatoire de la Cote d'Azur, CNRS, 06304 Nice, France.

Introduction: The unique oxygen isotopic signatures of Solar System bodies has presented a problem for the impact hypothesis for the formation of the Moon [1, 2]. In order to create an iron-poor Moon and simultaneously reproduce the angular momentum of the Earth-Moon system, early models required a glancing blow by a Mars-sized impactor that resulted in Moon being composed mainly of impactor material [3]. Therefore, in the general case, Moon and Earth should not be identical in their oxygen isotopic compositions. Nonetheless, until recently, Moon and Earth have been found to be indistinguishable in their oxygen isotope ratios. Proposed higher-energy giant impacts offer potential solutions to this conundrum [4], although at the expense of the need to shed substantial angular momentum from the system via orbital resonances [5]. More recently, some high-precision measurements on lunar samples indicated that the Moon has a greater Δ'^{17}O than Earth by 12 +/– 3 ppm [6], suggesting a heterogeneous Earth-Moon system.

Oxygen Isotope Mass Balance: The importance of differences in Δ'^{17}O between Earth and Moon can be assessed by considering contours for $\Delta'^{17}O_{Moon} - \Delta'^{17}O_{Earth}$ plotted as functions of the difference in Δ'^{17}O between Theia and the proto-Earth and the difference in the fractions of Moon and Earth inherited from Theia (Fig. 1, lower panel). The mass-balance equation plotted is

$$x_{Theia,\,Moon} - x_{Theia,\,Earth} = \frac{\Delta'^{17}O_{Moon} - \Delta'^{17}O_{Earth}}{\Delta'^{17}O_{Theia} - \Delta'^{17}O_{proto\text{-}Earth}} \quad (1)$$

where $x_{Theia,i}$ refers to the oxygen fraction of body i derived from Theia (essentially mass fractions of the bulk silicate portions of the bodies). For convenience, we also use the fractional difference δ_{Theia} rather than the absolute difference in Eq. 1:

$$\delta_{Theia} = (x_{Theia,\,Moon} - x_{Theia,\,Earth}) / x_{Theia,\,Earth}\,. \quad (2)$$

The implications of a difference in oxygen isotopic composition between Moon and Earth depend on the fraction of Theia contained within Earth (Eqs 1 and 2). Four recent proposed giant impact scenarios [1, 4, 5, 7] predict disparate differences in the Theia fractions in Moon and Earth (horizontal lines in Fig. 1). If the difference in Δ'^{17}O between Theia and the proto-Earth was zero, there is no oxygen isotope constraint on δ_{Theia} (Fig. 1). Similarly, if Earth and Moon are composed of precisely the same concentrations of Theia, there is no constraint on differences in Δ'^{17}O between Theia and the proto-Earth. Contours in Figure 1 indicate all cases in between.

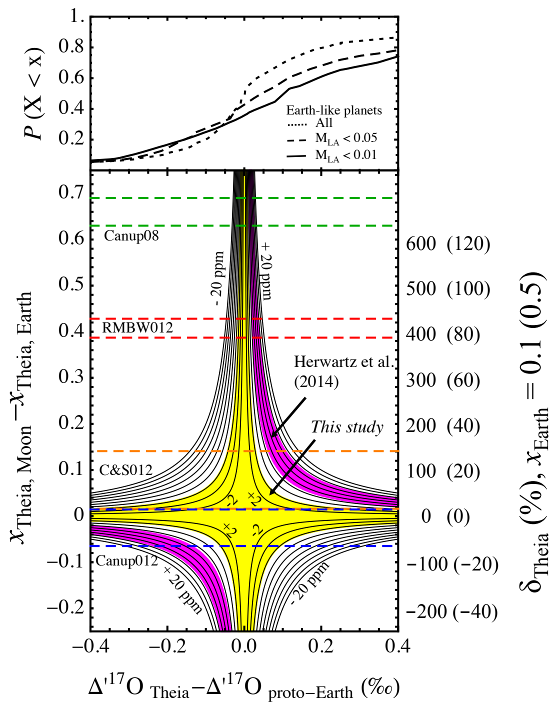

Figure 1. Contours of $\Delta'^{17}O_{Moon} - \Delta'^{17}O_{Earth}$ in ppm versus fractional differences in Theia content of the bulk silicate Moon and Earth and $\Delta'^{17}O_{Theia} - \Delta'^{17}O_{proto\text{-}Earth}$. The contour interval is 2 ppm.

A positive Δ'^{17}O of 12 +/– 3 ppm for the Moon [6] requires a difference in the proportions of Moon and Earth composed of Theia as indicated by the fact that the contours representing this range of values (violet regions, Fig. 1) do not include the center of the diagram. The relatively large δ_{Theia} values required would effectively remove the constraint imposed by oxygen isotopes that the Earth-Moon system was well-mixed.

New Measurements: We analyzed seven Apollo 12, 15, and 17 lunar samples and one lunar meteorite and compared their $^{17}O/^{16}O$ and $^{18}O/^{16}O$ isotope ratios with those for a suite of terrestrial igneous samples.

We found no resolvable difference in $\Delta'^{17}O$ between lunar mantle melts represented by these basalts and terrestrial mantle and melts. The 1 to 4 milligram lunar samples include high-Ti mare basalts, low-Ti Mg-rich olivine cumulate basalts, a quartz normative basalt, and a highland anorthositic troctolite. No discernible difference exists in $\Delta'^{17}O$ between SC olivine and lunar basalts powders (–0.001 +/– 0.002 1se) or fused beads (0.000 +/– 0.003 1se). The mean for all mafic terrestrial samples, representing terrestrial mantle and its melt products, is 0.000 +/- 0.001 ‰ (1se). Adding in quadrature the analytical uncertainty in the SC olivine and the standard error for the lunar samples yields a difference between lunar basalt and SC olivine of –0.001 +/– 0.0048 ‰ (–1 ppm +/–4.8 ppm, 2se), indistinguishable from zero.

Planetary Accretion: We used a planetary accretion model [8] that utilizes N-body accretion simulations based on the Grand Tack scenario [9] to model the expected differences in $\Delta'^{17}O$ between Theia and the proto-Earth and therefore the significance of our results. Our model differs from previous efforts in that we strictly limit our analysis to simulations that closely reproduce the current masses and locations of Earth and Mars and the oxidation state of Earth's mantle, we use a multi-reservoir model (composed of silicate, oxidized iron, and water) to describe the initial heliocentric distribution of oxygen isotopes, and we include the effects of mass accretion subsequent to the Moon-forming impact. An example simulation (Fig. 2), and others like it, shows that the $\Delta'^{17}O$ values of the colliding bodies rise together as the average $\Delta'^{17}O$ values increase during accretion. Incorporation of more material from greater distances from the Sun as accretion proceeds accounts for the rise. Large planets like Earth and Venus reflect an average of many embryos and planetesimals and so exhibit similar $\Delta'^{17}O$ values with time, while stranded embryos averaging fewer components, like Mars, show greater variation.

The cumulative distribution of $\Delta'^{17}O$ differences between Theia and proto-Earth is shown for 236 simulations of planet growth [10] in the upper panel of Fig. 1. The median $\Delta'^{17}O_{Theia} - \Delta'^{17}O_{proto\text{-}Earth}$ is nearly 0 in these calculations for all simulations (Fig. 1). However, our median predicted $\Delta'^{17}O_{Theia} - \Delta'^{17}O_{proto\text{-}Earth}$ is +0.1 ‰ if we restrict our analysis to those simulations consistent with adding ≤ 1% by mass of the late veneer of primitive material post Moon-forming giant impact as required by HSE concentrations [11]. This median value combined with our measurement of $\Delta'^{17}O_{Moon} - \Delta'^{17}O_{Earth}$ corresponds to δ_{Theia} of +20% to –60 % for the Mars-sized impactor scenario and +8% to –12 % in the proto-Earth sized impactor scenarios. The corresponding values for δ_{Theia} using the previous 12 +/– 3 ppm difference between Moon and Earth $\Delta'^{17}O$ values [6] are +80 to +180% and +16 to +36 %, respectively (Fig. 1A). The new measurements presented here are consistent with Earth and the Moon having identical Theia contents. Indistinguishable $\Delta'^{17}O$ values of Moon and Earth to the 5 ppm level of uncertainty is consistent with a Moon-forming impact that thoroughly mixed and homogenized the oxygen isotopes of Theia and proto-Earth. Our measured value for $\Delta'^{17}O_{Moon} - \Delta'^{17}O_{Earth} = 0$ (28) also requires that late-veneer impactors had average $\Delta'^{17}O$ values within ~ 0.2 ‰ or less of Earth, similar to enstatite chondrites.

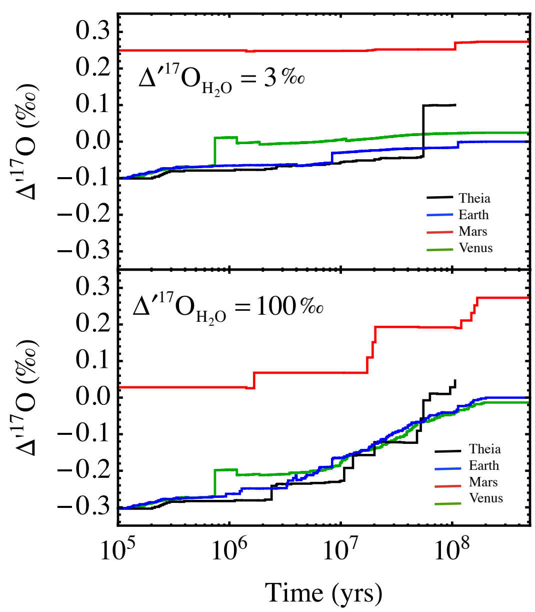

Figure 2. Simulation of oxygen isotope variation with time during accretion of Earth, Mars, Venus, and Theia.

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