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Light Hydrogen in the Lunar Interior: No One Expects the Theia Contribution

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Abstract

The Moon is thought to have formed after a planetary embryo, known as Theia, collided with the proto-Earth over 4.5 billion years ago. For the first time, we use H isotopes to help constrain the composition of Theia. We suggest the Moon incorporated very low-D/H (δD ≈ -750‰) hydrogen derived from solar nebula H_2 ingassed into the magma ocean of a large (~0.4 M_E), enstatite chondrite-like planetary embryo that was largely devoid of chondritic water. These new constraints have profound implications for the Moon-forming impact and the evolution of the Earth-Moon system.

1. Introduction

Apatite [$Ca_5(PO_4)_3(OH,F,Cl)$] is the only water-bearing mineral found in lunar samples. Hydrogen isotopic measurements of apatites in lunar rocks show that there seem to be multiple H reservoirs with diverse D/H ratios within the lunar interior, e.g. [1]. Intriguingly, apatite in the KREEP-rich Apollo 15 quartz monzodiorites (QMDs) has low water content (40-300 ppm) and δD as low as -750‰ (**Figure 1**) [2], which is almost as low in D as protosolar H or solar wind. However, their unique formation environment deep in the lunar crust makes it unlikely they incorporated solar wind, and instead they seem to sample H indigenous to the lunar interior [1]. We propose a new hypothesis for Theia's composition to explain this ultralow D reservoir (**Figure 2**).

2. Ingassed Solar Nebula Hydrogen

Recent work by Wu et al. [3] proposes that Earth contains solar nebula hydrogen and ^{3}He and ^{22}Ne, ingassed into the magma ocean of its largest embryo due to a ~1 bar H_2 atmosphere in contact with solar nebula gas. This requires a large embryo, > 0.3 – 0.4 M_E [7], during the first few Myr of the solar nebula. Wu et al. [3] argued that ~0.14 oceans (1 ocean = 1.5 × 10^{21} kg) solar nebula hydrogen with D/H=21 × 10^{-6}, combined with ~8 oceans of chondritic water with D/H=140 × 10^{-6}, leading to some materials with D/H=120 × 10^{-6} (δD≈-230‰) that should reside at the Earth's core-mantle boundary. The discovery of samples with δD≈-218‰ in terrestrial lavas sampling deep-mantle plumes [8] may support this hypothesis.

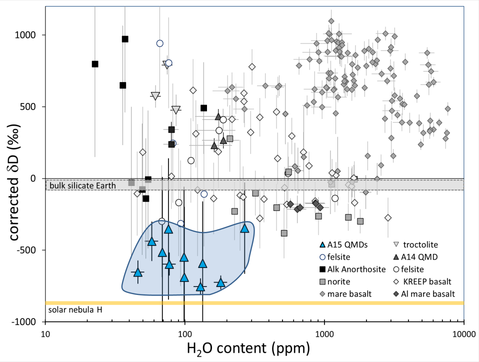

Figure 1: D/H ratios in lunar samples (data from[1] and references therein). The Apollo 15 QMDs are outlined in blue and extend to very low D/H (δD≈-750‰).

The Moon formed too late to ingas nebular H directly, but could not have inherited its lowest δD material from Earth [3]. This leaves ingassing into the magma ocean of Theia (the impactor) as the only plausible source of D-depleted nebular hydrogen. Ingassing into Theia's mantle could yield materials with δD≈-750‰, but requires it to be large enough to attract a significant atmosphere (> 0.3–0.4 M_E) [7] and accrete little (<200 ppm) chondritic water, as to not dilute the nebular signature. Such a massive Theia is consistent with the merger model [4], or possibly the hit-and-run model [5]. Enstatite chondrites (ECs) are extremely dry with oxygen fugacity 5 log units below the iron-wüstite buffer (IW-5) are consistent with this dry composition [3, references therein]. We model proto-Earth's mantle with ~1800 ppm H_2O and bulk δD≈+25‰, before core formation, and Theia's mantle with ~180 ppm H_2O and bulk δD≈ -610‰, before core formation, and ~100 ppm H_2O after core formation (Figure 2)

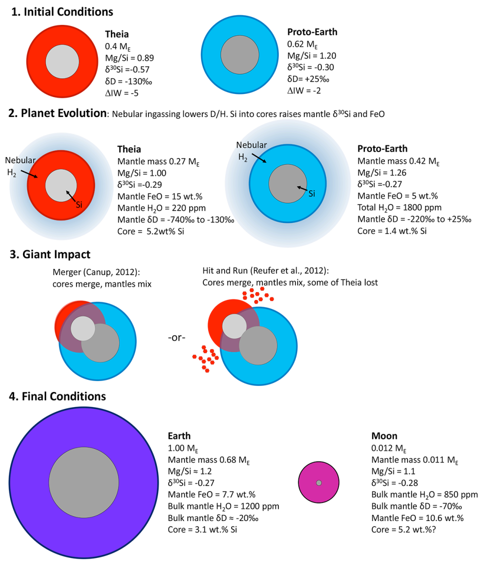

Figure 2: Our hypothesized sequence of events leading to the Moon's formation, starting with a massive and chemically reduced Theia colliding into a proto-Earth that already had accreted carbonaceous chondrite material.

3. An Enstatite Chondrite Theia

The similarity in multiple stable isotopes (ε^{48}Ca, ε^{64}Ni, ε^{92}Mo, Δ^{17}O, ε^{50}Ti, ε^{54}Cr, ε^{96}Zr, ε^{182}W; [3, references therein]) between the Earth and Moon is a long-standing mystery. If Theia is made of EC material, and the mixing parameter $|f_{PM}/f_{PE} - 1| \leq 40\%$ (f_{PM}=fraction of Moon that is proto-Earth, f_{PE}= fraction of Earth that is proto-Earth), work by [6] demonstrates that all these similarities are explained.

As pointed out by Meier et al. [6], ECs are FeO-poor, and yet the Earth's mantle has 7.8wt.% FeO and the Moon's mantle is 10.6wt.% FeO [9]. It is likely that the Moon incorporated proportionally more material from Theia than Earth, implying Theia was FeO-rich. We show [2] that sequestration of 12% of Theia's Si in its core (consistent with equilibration at <20 GPa, 1800 K and IW-5) would lead to its mantle being 15 wt.% FeO, and would increase δ^{30}Si by 0.27‰. Equilibration in proto-Earth (~25 GPa, 2800 K, IW-2) would sequester only 3% of its Si, leading to its mantle being <5 wt.% FeO, and increasing δ^{30}Si by 0.03‰. For reasonable starting compositions, both proto-Earth and Theia (and therefore Earth and Moon) have δ^{30}Si≈-0.28‰ after core formation. In a collision with f_{PM}=36%, f_{PE}=60%, $|f_{PM}/f_{PE} - 1|$=40%, consistent with either "merger" [4] or possibly "hit-and-run"[5], Earth and Moon's mantles achieve their observed FeO, and Earth's core (the two merged cores) is 3.1wt.% Si.

4. Conclusions

A massive, EC-like Theia is consistent with many stable isotope similarities between the Earth and Moon [3,6]. For reasonable initial conditions [2], our model is also consistent with the mantle FeO content and δ^{30}Si values for the Earth and Moon, and Earth's core Si mass fraction, provided Si is sequestered in proto-Earth's and especially Theia's core, consistent with Theia's large and reduced nature. Because Theia accreted no carbonaceous chondrite material, Theia likely originated interior to Earth's orbit

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