THE ORIGIN OF THE MOON'S EARTH-LIKE ^{182}W ISOTOPIC COMPOSITION. R. A. Fischer[1], F. Nimmo[2], and D. P. O'Brien[3], [1]Harvard University, [2]University of California Santa Cruz, [3]Planetary Science Institute.

Introduction: Earth's Moon formed from a giant impactor ("Theia") striking the proto-Earth during its last stages of formation [1]. In the canonical model, the Moon formed primarily from Theia. However, the Earth and Moon have identical/near-identical isotopic compositions for most elements [e.g., 2 and references therein], posing a potential challenge for this model.

To address this apparent contradiction, several new models of Moon formation have been proposed, in which the Moon is made primarily of Earth materials, which may erase the memory of isotopic differences between Earth and Theia [3–4]. It has also been proposed that isotopic equilibration between the Earth and Moon occurred in the proto-lunar silicate vapor disk [5]. Alternatively, some studies have suggested that Earth and Theia had the same isotopic provenance, perhaps due to an isotopically homogeneous inner disk [2], to produce an isotopically Earth-like Moon regardless of mixing. Several studies quantified the probability of Earth and Theia having the same O isotopic composition, finding a low, non-zero probability [6–7].

However, the Earth and Moon also have almost identical ^{182}W isotopic compositions [e.g., 8]. Lithophile ^{182}Hf decays to siderophile ^{182}W with a half life of 9 Ma [e.g., 8]. Therefore, the Hf–W system is sensitive to timing and mechanisms of core formation and a planet's mass evolution, making it fundamentally different [e.g., 2] from the stable isotopes that have previously been modeled. By combining this powerful isotopic system with dynamically self-consistent accretion models, here we evaluate the probability of Earth and Theia having the same W anomaly (ε^{182}W).

Numerical Methods: Growth histories for Earth and Theia analogues were extracted from a suite of 100 *N*-body simulations [9], which produced 73 Earth-Theia pairs. Fifty of the simulations had Jupiter and Saturn on more circular orbits (CJS) from the Nice model, and fifty had Jupiter and Saturn on more eccentric orbits (EJS), similar to the modern-day. We are currently undertaking calculations using a suite of 16 *N*-body simulations of the Grand Tack model [10].

The output of these simulations is combined with a core differentiation model [11], in which bodies undergo pressure- (P) and temperature- (T) dependent metal–silicate equilibration with each impact. Many major, minor, and trace elements are tracked, and oxygen fugacity (fO_2) is evolved self-consistently [12]. The model of [11] was modified to include W partitioning as a function of P-T-fO_2 based on experimental data [13]. Between impacts, radiogenic ^{182}W is produced in the mantle, and with each impact, the ^{182}W abundance is modified by a core formation event. Adjustable parameters include the depth (P-T) of each equilibration step, the amounts of metal and silicate that equilibrate, the thermal profile, and initial fO_2.

Results: Looking first at the Earth analogues, we find strong tradeoffs between the effects of equilibration depth, amounts of metal and silicate equilibrating, and formation timescale. Due to these tradeoffs, many parameter combinations can produce an Earth analogue with an Earth-like W anomaly. Whole mantle equilibration requires 40% of incoming metal to equilibrate (k = 0.4) to match Earth's W anomaly, in agreement with [14], a lower bound on the average k. Equilibrating with less silicate allows higher k, for example k = 0.85 and equilibration with 3x the impactor's silicate mass. The depth of equilibration is adjusted to ensure reproduction of Earth's mantle W abundance.

We tested several of these parameter combinations on the corresponding Theia analogues to evaluate the probability of forming identical W anomalies. Figure 1 shows results for two different model cases (only Earth analogues with a late veneer mass <5% are shown [15], n = 43). Earth's isotopic composition is assumed to fall between two endmembers: that of the Earth including all of Theia and its late veneer, and that of the proto-Earth before accreting Theia or the late veneer, both evolved to the present. The two model suites in Figure 1 produce only three cases in which the range of Earth's possible isotopic composition overlaps that of Theia (crossing the 1:1 line), a probability of 2–5%. However, none of these matches also yields the actual Earth and Moon anomalies (1.9 ± 0. 1 and 2.0 ± 0.1, respectively, relative to CHUR [16–17]).

Figure 2 summarizes the six model suites explored thus far, showing the median difference between Earth (having accreted Theia and the late veneer) and Theia anomalies. Increasing initial fO_2 significantly lowers Theia's anomaly, but not enough to match Earth's. Initial oxygen fugacities of IW–2 and higher produce a poor match to Earth's composition, especially in terms of mantle FeO and trace element abundances. Increasing equilibration T by 500 K lowers Theia's anomaly, but again not enough to match Earth's. Increasing k from 0.4 to 0.85 and correspondingly reducing the mass of equilibrating silicate results in a much higher anomaly for Theia.

Discussion: There are two distinct reasons for the improbability of identical Earth and Theia W anomalies. First, it is highly unlikely that any two bodies have identical anomalies, due to the intricate dependency on accretion history, as shown by [18] in the Grand Tack case. Second, and more importantly, it is virtually impossible for two bodies of such different sizes to have similar anomalies, because the *P-T* conditions of their interiors are so different, resulting in very dissimilar W metal–silicate partitioning behavior.

Dauphas et al. [2] inverted for the required ε^{182}W of the proto-Earth and Theia in the canonical Moon formation model. They found solutions if Theia's core formed faster than Earth's, attributing the near-identical W anomalies of the Earth and Moon to coincidence, but they could not assess its probability. Using dynamical methods, we find that it is extremely low (Figure 1) [18]. Kruijer and Kleine [19] used statistical methods to show the improbability of the Earth and Theia having similar anomalies. Here we tested their calculations using dynamical models, finding good agreement with their results.

The 2–5% probability of Earth and Theia having the same anomaly is an extreme upper bound, requiring Earth to accrete a very specific fraction of Theia (and not matching the measured W anomalies).

The probability of Earth and Theia having the same W anomaly is expected to be similarly low in the Grand Tack model because it forms planets faster, requiring higher *k* (approaching *k* = 1) to reproduce Earth's anomaly [18]. Higher values of *k* worsen the discrepancy between Earth and Theia anomalies (Figure 2). The probability of identical anomalies is very low in the Grand Tack case even without taking into account the very different sizes (and thus W partitioning behavior) of Earth and Theia [18].

Therefore, we conclude that it is virtually impossible that Earth and Theia inherited the same W anomalies. The Hf–W system provides a more stringent test of Moon formation models, fundamentally different from stable isotopes that track isotopic provenance [e.g., 20]. With this stricter test, we can conclude that a similar isotopic provenance is insufficient to explain the Earth–Moon isotopic similarity. The Moon's Earth-like W anomaly must be due to either mixing of Earth and Theia materials (requiring that the Moon is mostly derived from Earth, since Theia's anomaly was likely very high), or isotopic equilibration in the proto-lunar silicate vapor disk.

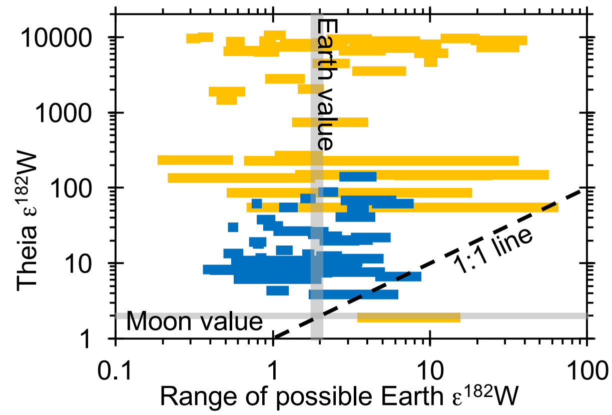

Figure 1: W anomalies for Theia and a range of possible Earth values for two model cases. Dark blue: $k = 0.4$, equilibration with whole mantle, initial fO_2 = IW–2.5. Yellow: $k = 0.85$, equilibration with 3x impactor silicate mass, initial fO_2 = IW–3.5.

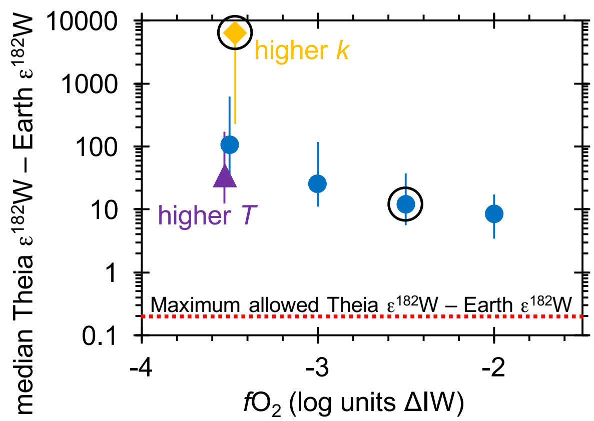

Figure 2: Median difference between Earth and Theia W anomalies. Blue circles: $k = 0.4$, whole mantle equilibration, variable initial fO_2. Purple triangle: same, but equilibration *T* +500 K. Yellow diamond: $k = 0.85$, equilibration with 3x impactor silicate mass. Black open circles: cases shown in Figure 1.

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