QUANTIFYING THE PROBABILITY OF THE EARTH AND MOON HAVING THE SAME TUNGSTEN ISOTOPIC COMPOSITION. R. A. Fischer[1] and F. Nimmo[2], [1]Harvard University Department of Earth and Planetary Sciences (rebeccafischer@g.harvard.edu), [2]University of California Santa Cruz Department of Earth and Planetary Sciences.

Introduction: The Moon is thought to have formed as a result of a giant impact on the proto-Earth [e.g., 1], but the exact nature of this impact and its consequences for the Moon's chemical composition remain enigmatic. One important clue to the Moon's origin is the observation that the Earth and Moon have identical/nearly-identical isotopic compositions for most elements that have been studied, such as O [e.g, 2–3], Ti [4], and W [5].

Canonical models of the Moon-forming impact indicate that the Moon formed primarily from material from the impactor ("Theia") [6]. Since all known Solar System bodies have unique isotopic compositions, the Earth–Moon isotopic similarity is thus not straightforward to explain. Several mechanisms have been proposed to resolve this apparent contradiction:

1. The proto-Earth and Theia did in fact have the same isotopic composition, possibly due to a common origin in an isotopically-homogeneous region of the inner disk [e.g., 7].
2. The Moon-forming impact was not consistent with the canonical model, and instead the Moon was formed from a mixture of proto-Earth and Theia material [8–9].
3. The Earth and Moon isotopically equilibrated post-impact [10–11].

In this study, we focus on testing the plausibility of mechanism #1. An isotopically-homogeneous inner disk can naturally explain isotopic similarity between the proto-Earth and Theia for most stable isotopes, but W provides a fundamentally different type of constraint. ^{182}Hf decays to ^{182}W with a half life of 9 Ma. Hf is lithophile and W is siderophile, making the Hf–W isotopic system sensitive to the timing and conditions of core formation [e.g., 12–13], not provenance. Here we model the evolution of this isotopic system in the Earth and Moon to quantify the probability of the Moon obtaining an Earth-like tungsten anomaly.

Numerical Methods: Mass evolution histories of the Earth and Theia were extracted from a suite of 100 *N*-body simulations of terrestrial planet accretion forming 73 Earth analogues, run in the EJS and CJS scenarios [14]. Theia was defined as the last body containing at least one planetary embryo to strike an Earth.

In the post-processing of the simulations, the compositions of the mantles and cores of Earth and Theia were tracked using a core formation model, which includes a variety of major, minor, and trace elements [15] as well as the Hf–W isotopic system [16]. Metal–silicate partitioning behaviors of all elements were based on experimentally-determined partition coefficients that evolve with pressure (P), temperature (T), oxygen fugacity (fO_2), and composition as a planet grows [e.g., 17–18]. The initial distribution of oxidation states in the disk was set to be IW–4 inside of 1.5 AU and IW–1.5 outside of 1.5 AU. This distribution was chosen because, when fO_2 is evolved self-consistently [e.g., 19], the FeO contents of both the terrestrial and Martian mantles are reproduced on average.

A Moon was formed from a portion of Theia equal to a lunar mass with 98% mantle and 2% core. This material was differentiated with a tungsten metal–silicate partition coefficient ($D_W = X_{Wmet} / X_{WO3sil}$) of either $D_W = 30$ or $D_W = 150$. The Earth's isotopic composition was calculated without late veneer accretion.

Results: The model was run for ten values of k = 0.1–1, where k is the fraction of incoming metal that equilibrates with the target's mantle. The depth of equilibration was varied along with k to ensure that Earth's mantle composition was always reproduced.

There are strong tradeoffs between the effects of equilibration depth, amounts of metal and silicate that equilibrate, and formation timescale in the Earth analogues [16]. Equilibration with the entire proto-Earth's mantle requires $k = 0.4$ on average, consistent with previous studies [e.g., 20], providing a lower bound on k. Equilibration with less silicate requires higher values of k to match Earth's isotopic composition.

Figure 1 illustrates the results for the Earth and Moon for $k = 0.4$ and whole mantle equilibration, in terms of the tungsten anomaly and $f^{Hf/W}$:

$$\varepsilon_{182W} = \left[\frac{(X^{182W}/X^{183W})}{(X^{182W}/X^{183W})_{CHUR}} - 1\right] \times 10^4$$

$$f^{Hf/W} = \frac{(X^{180Hf}/X^{183W})}{(X^{180Hf}/X^{183W})_{CHUR}} - 1$$

The pre-late veneer Earth and Moon are both taken to have actual values of $\varepsilon_{182W} = 2.2 \pm 0.15$ [21]. For this set of model conditions, Earth's tungsten anomaly and $f^{Hf/W}$ are reproduced on average (though the scatter is large), while those of the Moon are on average too high and low, respectively (Figure 1). The high model Moon ε_{182W} arises primarily because Theia grows rapidly [20], while the low $f^{Hf/W}$ is a consequence of Theia's core formation at relatively low P–T.

Figure 2 shows a histogram of the difference in tungsten anomaly between the Earth and Moon for both values of D_W and only including model Earths which have an ε_{182W} value similar to the measured value. In both cases, the Moon's anomaly is typically higher than that of the Earth by several epsilon units. A higher value of D_W during Moon formation produces larger anomalies in the Moon. For each value of D_W, we find one Earth–Moon match, for a probability of 4.5%.

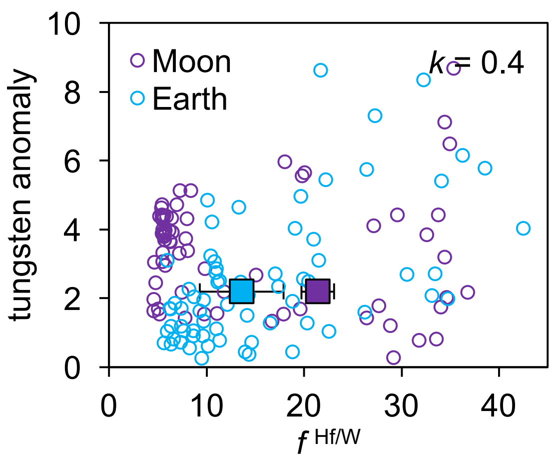

Figure 1: ε_{182W} and $f^{Hf/W}$ for the Earth and Moon. Filled squares: actual observed values. Open circles: model calculations. Calculations were performed for $D_W = 30$.

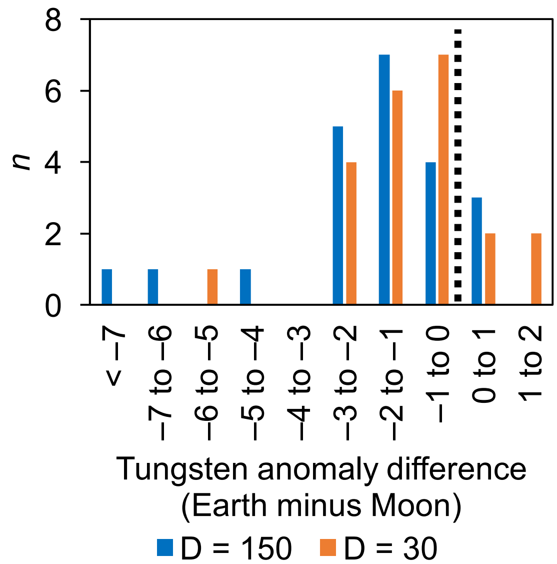

Figure 2: Difference in ε_{182W} in model Earth–Moon pairs that produce an Earth-like anomaly ($\varepsilon_{182W} = 2.2 \pm 0.15$; pre-late veneer). Results are shown for two different partition coefficients (D_W) of tungsten during lunar core formation. Vertical dotted line: Earth = Moon.

Discussion: We have evaluated the probability of the Moon and Earth having identical tungsten anomalies to within ±0.15 epsilon units. For cases in which the model Earth has an anomaly of 2.2 ± 0.15, the likelihood of a match with the Moon is 4.5%. This probability is the same for both values of D_W tested. In general, it is highly unlikely for any two bodies to have identical ε_{182W}, due to the intricate dependence on accretion history and core formation conditions.

Dauphas et al. [7] showed that it is possible for the Earth and Moon to have identical W anomalies if Theia's core formed faster than Earth's, but they could not quantify the probability of this happening, which we have done here. Kruijer and Kleine [22] argued that it is improbable for the Earth and Moon to have identical isotopic anomalies using statistical methods. We find good agreement with their results using dynamical models. The probability of the Earth and Moon having the same isotopic composition in the Grand Tack scenario is expected to be similarly low [23].

The Hf–W system provides a more stringent and fundamentally different test of Moon formation models than stable isotopes do. With a probability of 4.5% of the Earth and Moon obtaining the same tungsten isotopic composition by chance, mechanism #1 cannot be definitively ruled out. However, mechanism #2, forming the Moon from a mixture of proto-Earth and Theia materials [8–9], or mechanism #3, post-impact isotopic equilibration between the Earth and Moon [10–11], may be more robust. Future work should focus on quantifying the probabilities of these mechanisms producing the observed Earth–Moon tungsten isotopic similarity.

References: [1] Cameron A. G. and Ward W. R. (1976) *LPS VII*, 120–122. [2] Wiechert U. et al. (2001) *Science, 294*, 345–348. [3] Young E. D. et al. (2016) *Science, 351*, 493–496. [4] Zhang J. et al. (2012) *Nat. Geo., 5*, 251–255. [5] Touboul M. et al. (2007) *Nature, 450*, 1206–1209. [6] Canup R. M. and Asphaug E. (2001) *Nature, 412*, 708–712. [7] Dauphas N. et al. (2014) *PTRSA, 372*, 20130244. [8] Canup R. M. (2012) *Science, 338*, 1052–1055. [9] Ćuk M. and Stewart S. T. (2012) *Science, 338*, 1047–1052. [10] Pahlevan K. and Stevenson D. J. (2007) *EPSL, 262*, 438–449. [11] Lock S. J. et al. (2018) *JGR: Planet., 123*, 910–951. [12] Jacobsen S. B. (2005) *AREPS, 33*, 531–570. [13] Halliday A. N. and Lee D.-C. (1999) *GCA, 63*, 4157–4179. [14] Fischer R. A. and Ciesla F. J. (2014) *EPSL, 392*, 28–38. [15] Fischer R. A. et al. (2017) *EPSL, 458*, 252–262. [16] Fischer R. A. and Nimmo F. (2018) *EPSL, 499*, 257–265. [17] Fischer R. A. et al. (2015) *GCA, 167*, 177–194. [18] Shofner G. A. et al. (2014) *LPS XLV*, Abstract #1267. [19] Rubie D. C. et al. (2011) *EPSL, 301*, 31–42. [20] Nimmo F. et al. (2010) *EPSL, 292*, 363–370. [21] Kruijer T. S. et al. (2015) *Nature, 520*, 534–537. [22] Kruijer T. S. and Kleine T. (2017) *EPSL, 475*, 15–24. [23] Zube N. et al. (2017) *AGU Fall Meeting*, Abstract #P53F-05.