FORMATION SCENARIOS OF THE MOON: THE MESSAGE FROM TUNGSTEN ISOTOPES. Christoph Burkhardt[1] and Nicolas Dauphas[1], [1]Origins Laboratory, Department of the Geophysical Sciences, The University of Chicago, 5734 South Ellis Avenue, Chicago, Il 60637, USA (burkhardt@uchicago.edu, dauphas@uchicago.edu).

Introduction: While canonical giant impact models indicate that the Moon is mainly made from impactor material [*e.g.,* 1], the absence of isotope anomalies between the Moon and the Earth suggests that the Moon is mainly made out of terrestrial material [*e.g.,* 2]. An easy way out of this lunar isotope crisis is to assume identical isotope compositions for the impactor and the protoEarth [3]. This seems plausible, as the impactor and the protoEarth likely formed at similar heliocentric distances.

However, the within error identical $^{182}W/^{183}W$ ratios of the terrestrial and lunar mantles [4] have been used to argue against such a scenario. The W isotope composition in a body is altered by the decay of ^{182}Hf to ^{182}W ($t_{1/2}$= 8.9 Myr) and thus depends on the nature and timescales of accretion, core formation and mantle differentiation [e.g., 5]. It is considered an unlikely coincidence that a canonical Moon-forming impact produced identical W isotope compositions for the lunar and terrestrial mantles. Instead, W isotopes have been used to argue for a Moon predominantly derived from protoEarth material [2,5] or isotopic equilibration of the Moon and the Earth mantle in the aftermath of the giant impact [6].

Here, we investigate these qualitative claims by an advanced mass-balance that explores the Hf-W parameter space for the impactor and the protoEarth using the Hf/W ratios and the W isotopic compositions of the bulk silicate Earth and the Moon. Our mass-balance indicates that from a W isotope perspective, making the Moon mainly out of impactor material is as likely as making it primarily out of protoEarth mantle material.

Approach: The two observable constraints of the Hf-W system, the Hf/W ratio and the W isotopic composition of a reservoir are defined relative to a chondritic reference (CHUR) as:

$f=(Hf/W)_{reservoir}/(Hf/W)_{CHUR}-1$ and

$\varepsilon W=[(^{182}W/^{183}W)_{reservoir}/(^{182}W/^{183}W)_{CHUR}-1]\times 10^4$,

such that for a chondritic bulk planetary body at any time *t* after the start of the solar system $f=\varepsilon W=0$. The terrestrial and lunar mantles have within uncertainties identical W isotope compositions (εW_{Moon} =+2.0±0.1 [4] and εW_{BSE} =+1.9±0.1 [5]) and Hf/W ratios ($f_{Moon,mantle}$= 25.7±3.3 and f_{BSE}= 25.4±4.2, based on re-evaluation of literature estimates and using the chondritic Th/Hf and U/Hf ratios of [7]). We assume that the Moon-forming impact was the Earth's last major accretion event, followed only by accretion of a late veneer (0.33% of the mass of the Earth, 0.023% of the mass of the Moon [8]). We further assume that the impactor and the Earth have chondritic bulk compositions and that both bodies have identical silicate/metal (mantle/core) mass fractions, which seems plausible if they came from about the same heliocentric distance. The Moon is made out of protoEarth mantle, impactor mantle, impactor core and late veneer material. Of the impactor material in the Moon, a fraction is from the impactor core and the rest is from the impactor mantle. Metal in the lunar core probably corresponds to impactor core material (the lunar core represents ~2% of the mass of the Moon). The mass-fraction of the Earth derived from the impactor is kept constant at 0.11 (mars-sized impactor). Finally *k* is the fraction of the impactor core re-equilibrating with the Earth mantle before being absorbed into Earth's core, *i.e.*, *k*=1 indicates full equilibration of the impactor core with the target mantle and *k*=0 indicates no re-equilibration. For a given impact scenario and knowing f_{BSE}, εW_{BSE}, f_{Moon}, εW_{Moon}, the mass-balance equations can be solved numerically for $f_{impactor,mantle}$, $\varepsilon W_{impactor,mantle}$, $f_{protoEarth,mantle}$, $\varepsilon W_{protoEarth,mantle}$. All our simulations consider that the lunar core is made of impactor core material, which is suggested by all impact simulations [1,9,10,11] and is consistent with the near-terrestrial Fe/Mg ratio of the lunar mantle, which indicates that no iron reduction took place.

Results and discussion: *Canonical impact*: Solving the mass-balance for a canonical Moon-formation scenario (2/3 of the Moon derived from a Mars-sized impactor) and *k*=0.5 returns the impactor mantle and protoEarth mantle W isotope compositions and Hf/W ratios displayed in Fig. 1a,b. The dots represent 1000 outcomes of the calculation when uncertainties on the observables (*i.e.*, input parameters) are propagated using a Monte-Carlo simulation and the black crosses are the mean values. The inferred protoEarth and impactor mantles have considerably higher εW values than present-day terrestrial and lunar mantles. The εW of the protoEarth mantle strongly depends on the degree of re-equilibration of the impactor core. Varying *k* between reasonable estimates of 0.2 and 0.8 [12] yields protoEarth mantle εW values between +3 and +7. The εW of the impactor mantle is +3 to +7.

Non-canonical impact: A non-canonical impact scenario in which the Moon is mainly made from protoEarth material was proposed by [10] to overcome the lunar isotope crisis [2]. For tungsten, such a scenario is

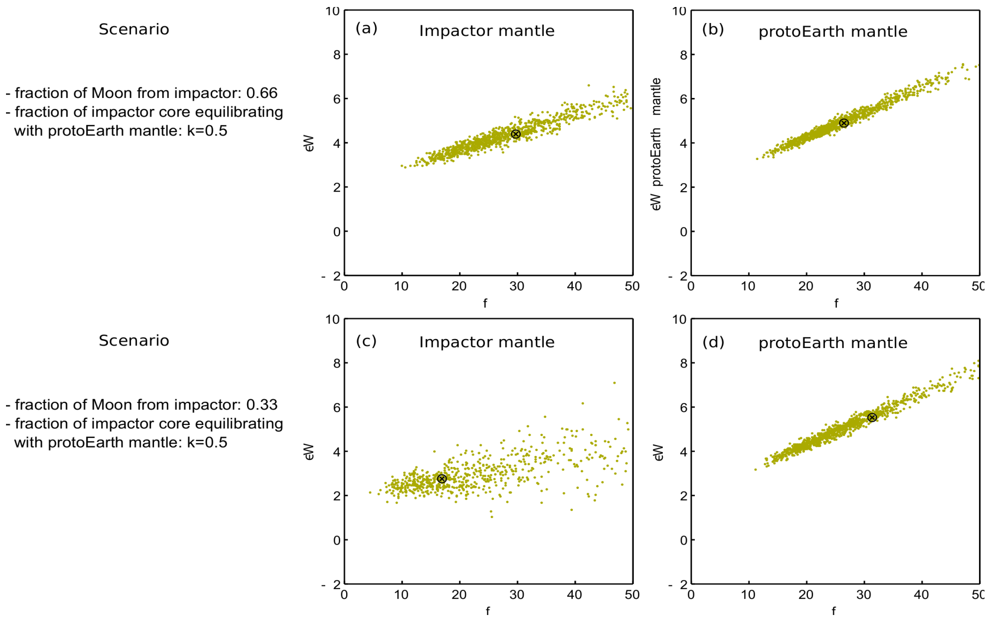

Fig. 1: W isotope compositions and Hf/W ratios of the moon-forming impactor and the protoEarth for a canonical (a,b) and non-canonical impact scenario (c,d).

not significantly different from the canonical model discussed above, except that the Hf-W systematics of the impactor can be less well constrained, because less impactor material ends up in the Moon. Mass-balance results for a scenario with the Moon being made by two thirds of protoEarth mantle material and all other parameters the same as in first scenario (*i.e.*, *k*=0.5) are shown in Fig. 1c,d. Such a scenario also requires mixing protoEarth and impactor materials with specific compositions to match the observed lunar and terrestrial mantle values.

Even if one assumes that the impactor core did not equilibrate with the protoEarth mantle (*i.e.*, fixing *k* to 0), which seems unlikely [12,13], deriving 100% of the lunar mantle from the protoEarth mantle does not resolve the W isotope conundrum because (i) the lunar mantle equilibrated with its core, which was derived from the impactor core, and (ii) the proportions of late veneer material in the lunar and terrestrial mantles were different. These two factors are sufficient to induce a significant shift in the lunar mantle composition, such that very specific protoEarth and impactor compositions are again required.

Conclusions: From the above observations it is evident that W isotopes do not provide strong constraints on which of the proposed models of the Moon-formation is correct. Both the canonical model of making the Moon mainly out of impactor material and the newer models in which the majority of the Moon is derived from the protoEarth mantle, require special conditions to explain the similarities in Hf/W ratios and εW values of the lunar and terrestrial mantles.

However, it should be noted that although special conditions are needed, the chances of producing post-impact planetary bodies with mantle εW ~2 do not seem too implausible. Simulations of planetary accretion result in planetary mantle εW values with a limited spread and a peak at εW ~2 [14,15]. Thus, from a dynamical perspective, producing bodies with mantle εW ~2 might be a natural outcome of planetary accretion. This view is supported by the fact that the mantle εW of Mars is also nearly indistinguishable from the terrestrial and lunar mantles (εW=2.6), despite having a very different Hf/W ratio and accretionary history [7,15]. Our results indicate that future high-precision measurements of lunar samples may reveal significant ^{182}W differences between the Earth and the Moon.

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