A NEW MODEL FOR LUNAR ORIGIN: ELEMENTAL AND ISOTOPIC CONSTRAINTS. S. B. Jacobsen[1], M. I. Petaev[1], B. Boatwright[1], S. J. Lock[1] and S. T. Stewart[2], [1]Department of Earth & Planetary Sciences, Harvard University, Cambridge MA 02138 (jacobsen@neodymium.harvard.edu); [2]Department of Earth and Planetary Sciences, University of California, Davis, CA 95616.

Introduction: The widely accepted model for the origin of the Earth-Moon system as the result of a Mars-sized giant impactor colliding with proto-Earth is inconsistent with a variety of new isotopic data. Generally, it is thought that the Earth and the Mars-sized Moon-forming impactor were isotopically different (for mass independent isotopic variations). Therefore, according to the "canonical" Moon forming SPH simulations, the Earth and the Moon should end up isotopically different from each other and that is inconsistent with observations. In contrast, isotopic studies have demonstrated that the Earth and Moon are remarkably similar in their isotopic compositions for many elements (notably mass independent isotopic compositions of O, Ti, Cr and W, and mass dependent isotope compositions of Mg and Si). This similarity between the Earth and Moon is unique in our Solar System when compared to other planetary bodies. In particular, the isotopic similarity in W isotopes and Hf/W ratios are unexpected, as this is a system that evolves with time after the formation of the solar system. It provides a fundamental constraint on the theory of the origin of the Moon; any successful model must properly explain such similarity between the Earth and Moon. We have developed a new model (see companion abstracts: [1-4]) that we believe is capable of meeting the isotopic, chemical and physical modeling constraints. In this model the Moon condenses out of bulk silicate Earth (BSE) vapor. The requirement is that the silicate Earth and impactor materials are shocked to a sufficiently high energy state such that upon adiabatic release to lower pressures this material forms a single phase fluid that bypasses the critical point and the Moon forms surrounded by 10's of bars of BSE gas. During Moon formation, the most volatile components stay in the vapor resulting in the well-known volatile element depletion of the Moon. Many siderophile elements are more depleted in the Moon's mantle compared to the Earth (Ni, Mo, Re) that has been taken as evidence for the formation of a small (few percent) lunar metal core after/during the formation of the Moon. We first discuss the constraints on the composition of the Moon and then we explore the case of the ^{182}Hf-^{182}W evolution as many previous studies have reported measurements that suggest that the ^{182}W/^{183}W isotopic compositions of the Earth and Moon are essentially the same; in addition their Hf/W ratios are similar. This is surprising in light of abundant evidence for a small lunar core. We show here that the inferred elemental composition of the Moon is consistent with the new model and that a small lunar core may only lead to insignificant effects in the Hf-W isotopic system while having major effects on elements like Mo.

The Bulk Silicate Composition of the Moon: The bulk silicate Earth (BSE) composition is compared with different estimates of the bulk silicate Moon (BSM) in **Figure 1** for the major, minor and selected trace elements. For the Earth we chose the widely used BSE composition of [5]. The gray band in **Figure 1** shows a range of estimates of the bulk Moon composition (BSM) normalized to the bulk silicate Earth. Our range of estimates of the bulk Moon composition is based on data and discussions provided by [6-17].
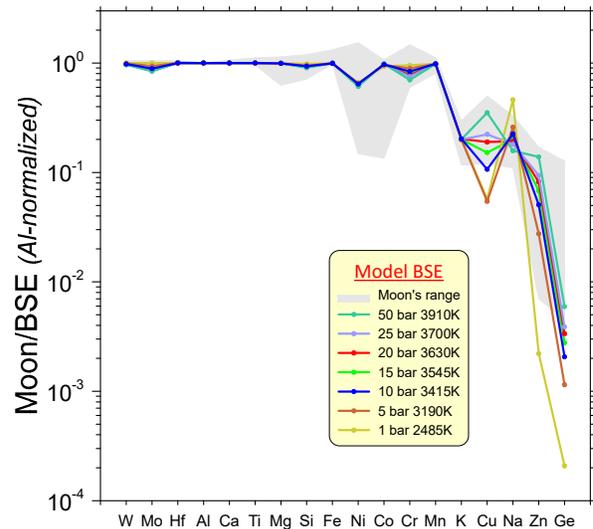

Figure 1: The grey band indicates the range of estimates for bulk lunar composition. Colored lines show predicted composition of the Moon from our model for a variety of conditions [3] and are consistent with our inferred BSM composition.

All BSM estimates are depleted in volatile elements (Na, K, Mn) relative to BSE, but there are substantial differences in Fe enrichment. The estimate of [10] reflects an early view that the Moon, in addition to volatile element depletion, is enriched in refractory elements and Fe (mg# = 84). Other early estimates, such as [7,9,12] predict similar enrichment in Fe, but not in refractory elements. Because olivines with mg# of 87.5 have been found in two old lunar rocks (troctolite 76535 and dunite 72415), it is difficult to understand how the bulk silicate Moon could have an Mg#

as low as 84. More recently [14,15,17] proposed BSM compositions with mg# of 87-90, similar to the Earth. Re-evaluation of lunar seismic data [18], and constraints from the recent GRAIL mission [19], now suggests a lunar crustal thickness of 30–40 km, half the thickness of Apollo-era estimates. Therefore, [16] no longer supports refractory element (Ca, Ti, Al) enrichment in the Moon. Compositions in **Figure 1** are normalized to the refractory element Al because Ca, Al, Ti and other refractory elements are believed to have close to chondritic ratios in both the Earth and the Moon [16]. The same is true for the refractory trace elements Hf, W, Mo and Pr. The refractory elements vary in a very small range due to the small uncertainties in various estimates of their chondritic ratios. The main planet-building elements Mg and Si have larger uncertainties because of the lack of samples that represent directly the lunar mantle composition. Fe is tied to Mg through the possible range of mg#'s. The Fe/Mn ratio of the BSE is about 60 while that of the Moon is about 75. The moderately volatile elements K and Na have depletion factors in the BM of 5 to 10, with K being particularly well established based on K/U ratios [10,16]. This is a major constraint on the model discussed in this paper. The colored lines in **Figure 1** show predicted composition of the Moon from our model for a variety of conditions and are consistent with our inferred BSM composition.
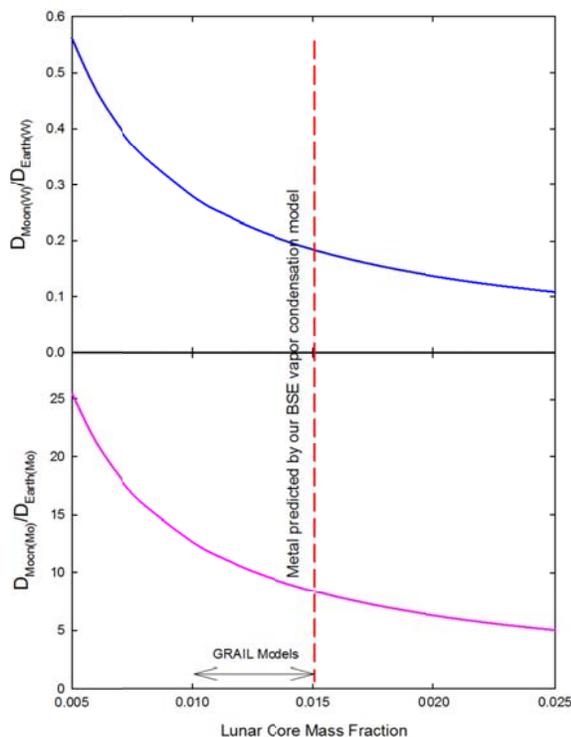

Figure 2: Calculated relationship between metal-silicate D-values for the Earth and Moon and the lunar

mass fraction as constrained by W isotopes, Hf/W and Pr/Mo ratios in the Earth, Moon and chondrites.

Lunar Core formation, the ^{182}Hf-^{182}W system and Pr-Mo fractionation: The $f^{Hf/W} \sim 18 \pm 2$ and $\varepsilon_{W(CHUR)} = +1.9 \pm 0.2$ are the same for both the Earth and Moon. In contrast, the $f^{Pr/Mo}$ of ~ 50 for the Earth and 750 for the Moon apparently reflect the effect of lunar core formation. Using these constraints we can calculate the metal silicate partition coefficient ratios, $D_{Moon(W)}/D_{Earth(W)}$ and $D_{Moon(Mo)}/D_{Earth(Mo)}$, as a function of the lunar core size. The results shown in **Figure 2** indicate the core size of $\sim 1.0 - 1.5$ % consistent with the recent GRAIL models and the amount of metal predicted by our BSE vapor condensation model. The behavior of Mo and W is different during core formation in the Earth and Moon. Mo is more siderophile during lunar core formation compared to the Earth's core formation, while the opposite is true for W. The values for the curves in the range 0.015 to 0.02 (**Figure 2**) are broadly consistent with experimental results on metal-silicate partitioning for W and Mo and earlier models for lunar core formation [20].

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