

TESTING MODELS OF LUNAR ORIGIN: K ISOTOPES, RADIOGENIC ISOTOPES, AND VOLATILE ELEMENTS. Stein B. Jacobsen¹ and M. I. Petaev¹, ¹Department of Earth and Planetary Sciences, Harvard University, 20 Oxford St., Cambridge MA 02138, USA (jacobsen@neodymium.harvard.edu).

Introduction: The Earth and Moon have unique chemical and isotopic signatures compared with other planetary bodies [1-4]. The Moon is depleted in volatile elements compared to Earth. K and Na are depleted by factors of ~5 to 10, while Zn, Cd, Pb, Bi and Tl are depleted by a factor of ~100. Any successful model for the origin of the Moon has to satisfy these chemical and isotopic constraints. It has long been thought to result from a catastrophic Moon-forming giant impact event [5]. The giant impact scenario predicts depletions of the most volatile species in the Moon, due to the high temperatures (>3000-4000 K) in the protolunar silicate vapor disk formed by this impact. Such depletions are also expected to lead to isotopic mass fractionation of the depleted elements in the Moon, with the Moon being expected to be isotopically heavier in these elements compared to the Earth. We are testing various options for the giant-impact hypothesis as the primary Moon-forming event and subsequent formation of the Moon itself in the proto-lunar silicate vapor disk generated by this impact by (1) modeling of the chemical and isotopic evolution of the proto-lunar silicate vapor disk, (2) analyzing K isotope composition of selected lunar samples [6], (3) using isotopic and chemical compositions of lunar samples to place tighter constraints on estimates of the Moon's chemical composition. We are exploring the range of chemical/isotopic disk models that are consistent with both the volatile element depletions and isotopic constraints.

Models and K isotopes: Because the K depletion in the Moon is sufficiently large, an isotope effect would be expected. Volatile-element-depleted bodies such as the Moon were expected to be enriched in heavy K isotopes due to the loss of volatiles. Recently [6], we reported new high-precision K isotope data for the Earth, the Moon and chondritic meteorites. We found that the lunar rocks are enriched in the heavy isotopes of K ($\delta^{41}\text{K}_{\text{BSE}}$) compared to the Earth and chondrites by around 0.4 per mil. The $\delta^{41}\text{K}_{\text{BSE}} = 0.4$ can be best explained as the result of the incomplete condensation of a bulk silicate Earth vapor at an ambient pressure higher than 10 bar. The constraints of the chemical loss and isotopic fractionation of K were used by [6] to compare two recent dynamic models put forward to explain the identical non-mass-dependent isotope composition of the Earth and the Moon. The first model (**Figure 1a**) explains the oxygen isotopic homogeneity ($\Delta^{17}\text{O}$) of the Earth and the Moon by

equilibration of both bodies through a silicate atmosphere [7]. However, it would result in zero or negative $\delta^{41}\text{K}$ values for the Moon, inconsistent with the positive value measured by [6]. However, the measured K isotope composition of the Moon is consistent with the recently proposed high-energy, high-angular-momentum giant impact model [8] (**Figure 1b**) that leaves the Earth in a state exceeding the hot spin stability limit, so the mantle, atmosphere and disk form a well-mixed continuous structure that extends beyond the Roche limit.

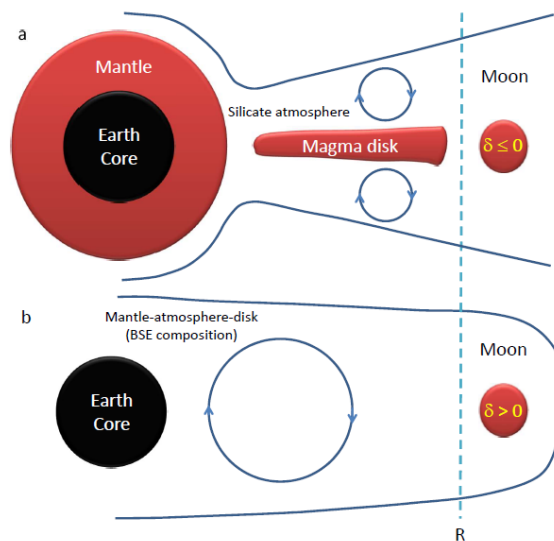


Figure 1. Models for the post-giant-impact state to explain the identical non-mass-dependent isotope compositions of the Earth and the Moon [6]. Material that forms beyond the Roche limit can produce the Moon. δ in the figure represents $\delta^{41}\text{K}_{\text{BSE}}$.

Pb isotopes: It is well established that the Pb isotope evolution of the Moon is drastically different from that of the Earth due to the severe depletion of Pb in the Moon. This is quantified in **Figure 2** which shows present values of mare basalts [9] resulting from a bulk silicate Moon (BSM) evolution with $^{238}\text{U}/^{204}\text{Pb} = 300$ (+/-200) compared to the bulk silicate Earth (BSE) value of about 8.5. Also shown is the Pb isotope evolution of the sources of orange and green glasses, because these materials supposedly argue for higher volatile contents of the Moon [14, 15]. Their evolution curves correspond to $^{238}\text{U}/^{204}\text{Pb}$ of 30 [10] and 20 [11] for the orange glass source (OGS) green glass source (GGS), respectively.

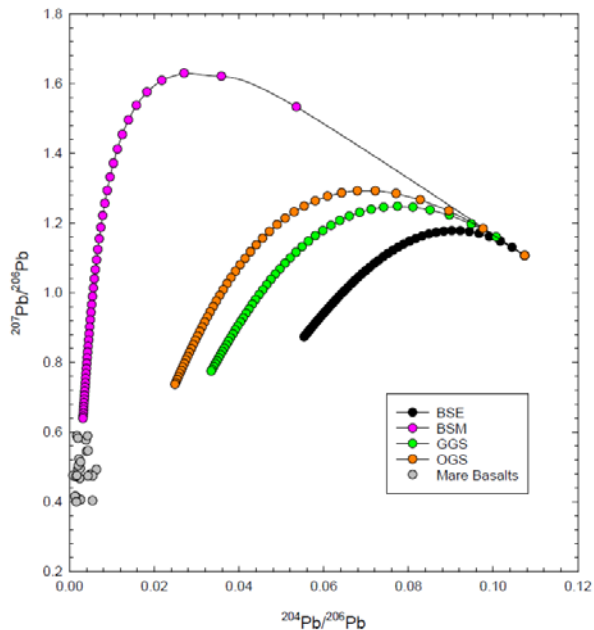


Figure 2. Pb isotopes in the Moon compared to the Earth.

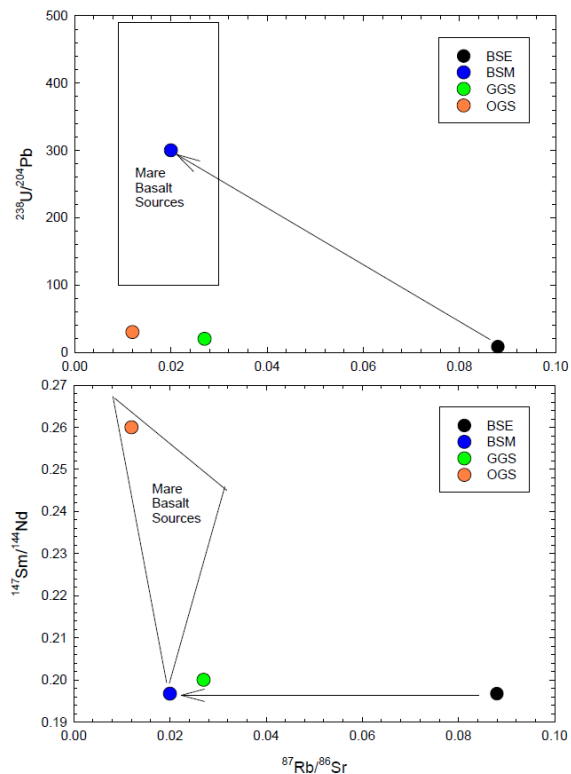


Figure 3. Comparison of Sr, Nd and Pb isotope constraints on element fractionation in lunar sources compared to the Earth.

Nd, Sr, and Pb isotope constraints: The Sr isotope evolution of mare basalt sources [9] constrain the bulk silicate Moon $^{87}\text{Rb}/^{86}\text{Sr}$ to ~ 0.02 . **Figure 3** com-

pares this value to Rb/Sr and Sm/Nd of orange and green glass sources [12] as well as to their U/Pb. The arrows show the change in Rb and Pb concentrations during the formation of the Moon.

Models and volatile element pattern of the Moon: We used the isotopic constraints on Rb/Sr and U/Pb, combined with estimates of the K [13], S [14], and H_2O [14, 15] depletion in materials representing BSM, GGS and OGS to calculate their depletion patterns (**Figure 4**). The BSM volatile element pattern can be well understood in terms of the Moon formation model [8] depicted in **Figure 1b**. The progressive enrichment in more volatile elements in the OGS and GGS is inconsistent with condensation. These enrichments are most likely inherited from late volatile-rich impactors. Therefore the OGS and GGS patterns represent only local sources and should not be used in BSM estimates. This also means that the Moon has very low water content that should be at least as depleted as Pb.

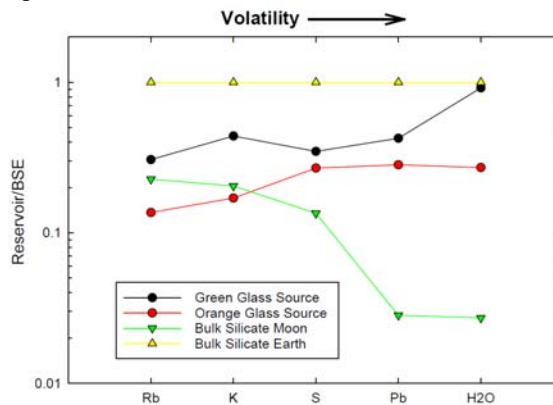


Figure 4. Depletion patterns of BSM, GGS and OGS.

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