

**RUBIDIUM ISOTOPIC COMPOSITIONS OF EARTH, MOON AND CHONDRITES.** N. X. Nie<sup>1,2</sup>, T. Hopp<sup>1</sup>, and N. Dauphas<sup>1</sup>, <sup>1</sup>Origins Laboratory, Department of the Geophysical Sciences and Enrico Fermi Institute, The University of Chicago, Chicago, IL 60637, USA, <sup>2</sup>Geophysical Laboratory, Carnegie Institution for Science, Washington, DC 20015, USA. (nnie@carnegiescience.edu).

**Introduction:** Terrestrial planets are all depleted in moderately volatile elements (MVEs) such as K, Rb, Cu, and Zn compared to their chondritic building blocks [1, 2]. In addition, the Moon is also depleted in MVEs compared to the Earth, which most likely reflects volatile loss during the Moon-forming “giant impact”. The mechanisms that led to the volatile element depletion in planetary bodies remain largely unknown. Nevertheless, identifying these mechanisms will provide considerable information regarding the accretion, formation, and evolution of planetary bodies and the early Solar System.

K and Rb are two MVEs that are most suitable for studying volatile depletion processes since they are both lithophile (as opposed to siderophile and chalcophile), meaning that they are preferentially enriched in the silicate part of differentiated planetary bodies and are not affected by core formation. During evaporation, their volatilities can lead to significant loss accompanied by isotopic fractionation that reflects the volatilization conditions. Recent high-precision isotope measurements on K and Rb showed resolvable isotopic variations among planetary bodies [3-7], the data is however still limited, especially for Rb isotopes.

Here we report new high-precision Rb isotopic data on chondrites. Together with the previously reported Rb isotopic compositions of the Earth-Moon system in [7], we discuss the Rb isotopic variations in these planetary bodies and the possible causes.

**Samples and Methods:** Chondrite samples including carbonaceous chondrites (CCs), ordinary chondrites (OCs), and enstatite chondrites (ECs) were measured for Rb isotopic compositions (Fig. 1). All selected samples are meteorite falls, hence, potential effects of terrestrial weathering on the Rb isotopic compositions are limited. Rubidium purification and isotope measurements were done in the Origins Lab at the University of Chicago, following the method described in [7]. Rubidium isotopic compositions are reported using the traditional delta notation ( $\delta^{87/85}\text{Rb}$ ), relative to the reference standard NIST SRM 984.

**Results and Discussion:** Large Rb isotopic variations were observed, ranging from -1 to +0.3 ‰ (Fig. 1). Below we discuss the Rb isotope data by chondrite groups and the Earth-Moon system.

**Carbonaceous Chondrites (CCs).** Eight CCs were measured, including two CIs, two CMs, two CVs, and two COs. The Rb isotopic variation among them is rather limited, about 0.2 ‰. Within-group variations are

also insignificant, so the Rb isotopic compositions of the samples should reflect their parent body compositions. Despite of the limited variation, there is a trend among different CC groups in which the  $\delta^{87/85}\text{Rb}$  value and the Rb concentration decrease in the order CI > CM > CV > CO. Such trends have also been observed for another volatile element Zn [8]. One possible explanation of these trends is two component mixing of volatile-rich, CI-like matrix with a volatile-depleted component that has an isotopically light composition (e.g., chondrules or calcium-aluminum-rich inclusions).

**Ordinary Chondrites (OCs).** Seven OCs from H, L, and LL sub-groups with different metamorphic grades were measured, and they display extremely large Rb isotopic variation. Interestingly, the more metamorphosed samples (H6, L5, LL6) have isotopic compositions more similar to CCs, but the less metamorphosed (H4, L4, LL3.2, LL4) show very scattered and light Rb isotopic compositions down to -1 ‰. Fairly large K isotopic variation (0.5 ‰ or larger) among OCs has also been observed [9]. One possible interpretation for the observed Rb isotopic variation is that less metamorphosed OCs may reflect initial isotopic heterogeneity, while the larger degree of metamorphism led to homogenization and less variation in the Rb isotopic compositions of more metamorphosed ones. The large isotopic variation of OCs makes it difficult to constrain the OC parent body composition. More work is needed to test if increasing the analyzed masses can alleviate this isotopic heterogeneity. Another complication is that almost all OCs have experienced fluid alteration to some extent, even the most pristine ones. Redistribution of Rb and K during fluid alteration will need to be taken into account when interpreting their isotopic compositions.

**Enstatite Chondrites (ECs).** Among the five analyzed ECs, the two less metamorphosed ones (EH4) have Rb isotopic compositions similar to the Earth, the more metamorphosed ECs (EH5 and EL6) have heavier Rb isotopic compositions. Average K isotopic composition of ECs shows similarity to that of the Earth but with large variations [5]. If the Rb isotopic compositions of EH4 represent the primary signature, this would imply that Rb isotopic composition was not much fractionated during Earth formation despite of Rb volatile loss. No systematic correlation between  $\delta^{87/85}\text{Rb}$  values and Rb/Sr ratios was found, implying that the heavier Rb isotopic compositions of EH5 and EL6 cannot be simply explained by volatile loss during metamorphism.

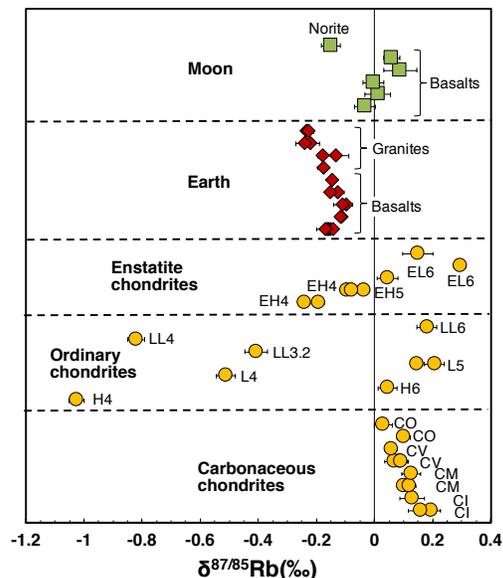


Fig. 1 Rb isotopic compositions of chondrites, Earth and Moon. Earth and Moon data are from [7].

**Earth-Moon system.** The Rb isotopic compositions of the Moon and Earth can provide insights on why the Moon is depleted in MVEs compared to the Earth [7]. Using the Rb isotopic compositions of lunar and terrestrial basalts to represent the bulk Moon and bulk Earth respectively, the Moon is enriched in heavy Rb isotopes compared to the Earth, by  $+0.16 \pm 0.04$  ‰. This heavy isotope enrichment is best explained in a scenario where kinetic (as opposed to equilibrium) evaporative loss of Rb occurred (one possible setting would be evaporation of Rb from magma into vapor in the protolunar disk after the giant impact). This is because isotope fractionation should be much smaller if only equilibrium fractionation was involved (e.g.,  $\sim 0.03$  ‰ Rb equilibrium isotopic fractionation between silicate melt and vapor at 1500 K), and in a condensation regime, kinetic isotope fractionation would enrich the condensed material in light isotopes, which is opposite to the observation that the Moon is isotopically heavier than the Earth.

The observed Rb isotopic fractionation between the Moon and Earth can be used to constrain the saturation level of Rb ( $S_{Rb}$ ) in the vapor during Rb evaporation. This is because if Rb is fully saturated in the vapor, the Rb isotopic fractionation between vapor and residue would be controlled by equilibrium fractionation. On the other hand, evaporation into vacuum (zero saturation) would show the largest isotopic fractionation with the ideal kinetic isotope fractionation factor ( $\Delta_{kin,Rb}$ ).

Mathematically, this relationship can be expressed as  $\delta_{i,Moon} - \delta_{i,Earth} \approx (1 - S_i) \Delta_{kin,i} \ln f_i$  for the Earth-Moon system, where  $S_i$  is the saturation level of an element  $i$  in the vapor ( $S_i = P_i/P_{i,sat}$ , i.e., the pressure of the element in the vapor ( $P_i$ ) divided by its saturation vapor pressure

( $P_{i,sat}$ )),  $\Delta_{kin,i}$  is the kinetic isotope fractionation factor during vacuum evaporation, and  $f_i$  quantifies the depletion of the element in the Moon compared to the Earth and is calculated by dividing the concentration of the element in the Moon by its concentration in Earth. Equilibrium fractionation factor ( $\Delta_{eq,i}$ ) is neglected here due to its very small value compared to  $\Delta_{kin,i}$  at high temperature.

Using the equation above, a vapor saturation level of  $\sim 99\%$  for Rb ( $S_{Rb} = 0.99$ ) was obtained (note that despite of the high level of saturation the isotopic fractionation is still not equilibrium which only occurs when  $S = 1$ ). Applying the equation to other elements gives the same level of saturation. Based on the equation, by plotting  $\delta_{i,Moon} - \delta_{i,Earth}$  vs.  $\Delta_{kin,i} \ln f_i$ , elements should follow a straight line with a slope of  $1 - S$  if they were at the same level of saturation. As shown in Fig. 2, they do plot on a straight line corresponding to a saturation level of 99%.

The same level of vapor saturation for all these elements with contrasting volatilities points to one big event which controlled the volatile element depletion and isotope fractionation of the Moon (elements won't necessarily follow the same trend if secondary processes are major controlling factors), and we attribute this to the viscous drainage of the vapor in the proto-lunar disk carrying volatile elements evaporated from the underlying magma to the Earth, which could be achieved if the disk was controlled by magnetorotational instability (see [7] for details).

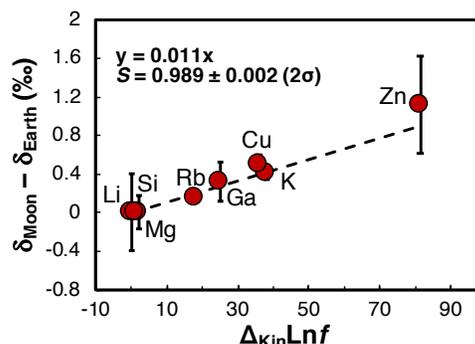


Fig. 2 Elements in the Moon follow the same trend with regard to their depletions and isotopic fractionations relative to the Earth, which can be explained by the same level of saturation of these elements ( $S = 0.99$ ) in the vapor of the protolunar disk after the giant impact. See [7] for details.

**References:** [1] Halliday A. N. and Porcelli, D. (2001) *EPSL*, 192, 545–559. [2] Davis A. M. (2006) in *Meteorites and the Early Solar System II*, 1, 295–307. [3] Wang K. and Jacobsen S. B. (2016) *Nature*, 538, 487. [4] Tian Z. et al. (2019) *GCA*, 266, 611–632. [5] Zhao C et al. (2019) *Meteoritics & Planet. Sci.*, in press. [6] Pringle E. A. and Moynier F. (2017) *EPSL*, 473, 62–70. [7] Nie N. X. and Dauphas N. (2019) *ApJL*, 884(2), L48. [8] Pringle E. A. et al. (2017) *EPSL*, 468, 62–71. [9] Ku Y. and Jacobsen S. B. (2019) *LPSC*, Abstract #1675.