

**LUNAR ORIGIN BEYOND THE HOT SPIN STABILITY LIMIT: STABLE ISOTOPIC FRACTIONATION.** S. Huang<sup>1</sup>, M. I. Petaev<sup>2,3</sup>, W. Wang<sup>4</sup>, S. J. Lock<sup>2</sup>, Z. Wu<sup>4</sup>, S. T. Stewart<sup>5</sup> and S. B. Jacobsen<sup>2</sup>, <sup>1</sup>Department of Geoscience, University of Nevada Las Vegas, [shichun.huang@unlv.edu](mailto:shichun.huang@unlv.edu) <sup>2</sup>Department of Earth and Planetary Sciences, Harvard University, <sup>3</sup>Harvard-Smithsonian Center for Astrophysics, <sup>4</sup>School of Earth and Space Sciences, University of Science and Technology of China, <sup>5</sup>Department of Earth and Planetary Sciences, University of California, Davis.

**Introduction:** As two of the most studied Solar System objects, the Earth and its Moon show great similarity in isotopic compositions [1-8]. However, since the Apollo era, it has been well known that the Moon is depleted in volatile elements (Na, K, Zn, etc.) compared to the Earth [2, 5]. Whether the depletion of volatile elements is coupled with isotopic fractionation (Zn, [5]) or not (K, [2]) is an important constraint on the formation of the Moon. Here we use a forward modeling approach to investigate the possible isotopic fractionation during the formation of the Moon. Specifically, we use chemical thermodynamics calculations [9-10] together with isotopic fractionation and mass balance to investigate the idea that the Moon may form in the vapor/magma disk surrounding the Earth subsequent to the Moon-forming giant impact [11-16]. We adopt the P-T condition obtained in [11] for a high energy, high angular momentum post-impact state, and use established principles of thermodynamics to calculate the composition of the Moon formed as condensate from a silicate atmosphere with a bulk silicate Earth composition (BSE). The compositional effect is presented in accompanying abstracts [9-10]. Here we discuss the mass-dependent isotopic effects during condensation from a silicate atmosphere.

**Chemical Equilibration in a New Lunar Origin Model:** The physical model is from Lock and his colleagues [9,11]. Specifically, the Moon formed after a high energy, high angular momentum impact. Such impacts lead the Earth to form a continuous structure of mantle, silicate atmosphere and disk in a state that exceeds the hot spin stability limit. The continuous mantle-atmosphere-disk structure cooled by radiation from the outer regions. Droplets condensed in the relatively low-P-T outer regions of this mantle-atmosphere-disk structure and fell inwards where they encountered the hotter and denser silicate vapor and reequilibrated with the gas phase. Droplets that fell inside the Roche limit were completely re-vaporized and homogenized with the gas phase; those that stayed outside the Roche limit formed the moonlets, which eventually accreted the Moon. Because of the energetic turbulence and convection within the mantle-atmosphere-disk structure, the gas phase remained chemically and isotopically homogeneous.

**Method:** In our current approach, there are only two phases: gas and moonlets (condensed phase). In

contrast, our previous approach [15-16] considered two condensed phases: reactive condensate and inert condensate, with the inert condensate forming the moonlets.

The chemical fractionation between the condensate and gas is constrained using a Gibbs free energy minimization model (an updated version of the GRAINS code) [10, 15, 17]. Isotopic fractionation between the condensed phase and the gas is calculated by using mass balance and mass dependent isotopic fractionation factors.

**Mass Dependent Isotopic Fractionation Factors:**

To the best of our knowledge, equilibrium mass-dependent isotopic fractionation factors between condensed and vapor phases are not experimentally determined. However, several first principles calculation studies provided such data for O, Mg, Si and Ca [18-21], and synchrotron radiation experiments for inelastic nuclear resonant X-ray scattering provide such data for Fe [22-23]. In detail, these approaches give mass dependent isotopic fractionation factors between common mantle minerals and atomic gases. While there are possible small isotopic fractionations among mantle minerals and between mantle minerals and basaltic melts, such fractionations are much smaller than those between condensed phases and atomic gases. Consequently, we use the isotopic fractionation factors between mantle minerals and atomic gases to be representative of isotopic fractionation factors between condensed and vapor phases (Fig. 1). Specifically, for O, Mg and Si, isotopic fractionation factors between olivine and atomic gases are used, while for Ca we use clinopyroxene data. Fe data for FeO (wustite) are used. In addition we performed new first principles calculations for K and Zn isotopic fractionation factors for K-spar and ZnS.

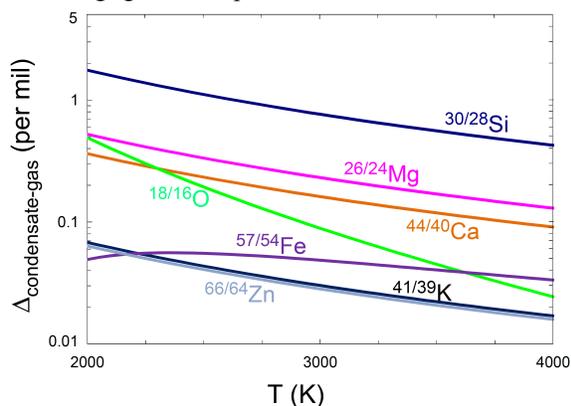
**Results and Discussion:** Si has the largest isotopic fractionation factor between the condensed phase and gas among the several elements discussed here across the whole temperature range concerned (Fig. 1). As expected, Si shows the largest isotopic effect during formation of the Moon (Fig. 2) [13, 16].

Fig. 2a shows the best fits for modeled lunar composition under a variety of pressures, 1 bar to 50 bar, model results from [9-10]. The model results at 10's bars reasonably reproduce the volatile element depletion of the Moon. Fig. 2b shows the corresponding

isotopic effects in the modeled lunar compositions. Pressure has limited effect on the modeled isotopic effects. Si shows the largest fractionation, with the Moon being predicted  $\sim 0.04$  per mil heavier than the Earth. Zn and K show the second and the third largest isotopic effect at 0.01-0.03 per mil level. All other elements have less than 0.01 per mil isotopic effects. Among the elements concerned here, the magnitude of the Si and Zn isotopic fractionation (0.02-0.04 per mil) predicted by our model are close to their current analytical precision.

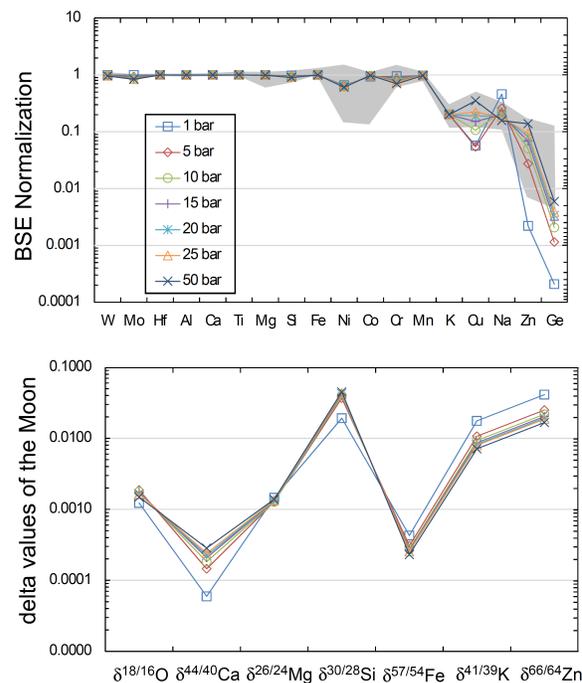
Our prediction of similar K isotopic compositions for the Earth and Moon is consistent with previous measurement, although with a relatively large error bar [2]. More updated high precision K isotopic work on lunar and terrestrial samples should shed more light on this issue [e.g., 24]. In contrast, Paniello et al. [5] argued that the Moon has a  $^{66}\text{Zn}/^{64}\text{Zn} \sim 1$  per mil higher than the chondritic reservoir and the Earth. Such a large Zn isotopic effect is not predicted by our calculation. A large Zn isotopic difference between the Earth (chondritic reservoir) and the estimated bulk Moon [5], if real, must imply that the Moon formed under very low pressure, i.e., a vacuum. It appears that the large Zn isotopic variation,  $\delta^{66/64}\text{Zn}$  ranging from -6 to +2, in lunar rocks represents re-distribution of Zn isotopes among surface samples during secondary processes, such as late bombardment; i.e., they are not a pristine signature. Consequently, the bulk Moon Zn isotopic composition, and probably isotopic compositions of all volatile elements, need to be carefully re-evaluated.

**Conclusions:** A new lunar origin model predicts that the Moon is a partial condensate of the bulk silicate Earth [9,10]. At the model pressures and temperatures of equilibration between the Moon and Earth, we predict negligible isotopic fractionation.



**Fig. 1** Calculated isotopic fractionation factors of O, Mg, Si, K, Ca, Fe and Zn between condensed and vapor phases in this study.

**References:** [1] Taylor S. R. and McLennan S. (2009) Cambridge University Press. [2] Humayun M. and Clayton R. N. (1995) *GCA* 59, 2131-2148. [3] Georg R. B. et al. (2007) *Nature* 447, 1102-1106. [4] Simon J. I. and DePaolo D. J. (2010) *EPSL* 289, 457-466. [5] Paniello R. C. et al. (2012) *Nature* 490, 376-379. [6] Sedaghatpour F. et al. (2013) *GCA* 120, 1-16. [7] Wiechert U. et al. (2001) *Science* 294, 345-348. [8] Wang K. et al. (2015) *EPSL* 430, 202-208. [9] Lock S. J. et al. (2016) *LPSC*. [10] Petaev M. I. et al. (2016) *LPSC*. [11] Lock S. J. and Stewart S. T. (2016) *LPSC*. [12] Pahlevan K. and Stevenson D. J. (2007) *EPSL* 262, 438-449. [13] Pahlevan K. et al. (2011) *EPSL* 301, 433-443. [14] Canup R. M. et al. (2015) *Nature Geosci* 8, 918-921. [15] Petaev M. I. et al. (2014) *LPSC* Abstract #2316. [16] Huang et al. (2014) *LPSC* Abstract #2246. [17] Petaev M. I. (2009) *Calphad* 33(2), 317-327. [18] Huang F. et al. (2013) *EPSL* 367, 61-70. [19] Huang F. et al. (2014) *EPSL* 140, 509-520. [20] Feng C. et al. (2014) *GCA* 143, 132-142. [21] Wu Z. et al. (2015) *EPSL* 409, 339-347. [22] Struzhkin V. V. et al. (2001) *Phys. Rev. Lett.* 87, 255501-1-4. [23] Struzhkin V. V. et al. (2004) *Hyp. Interac* 153, 3-15. [24] Wang K. et al. (2016) *LPSC*.



**Fig. 2** Chemical and isotopic data for modeled lunar compositions over the pressure range for lunar accretion in the new model of Lock et al. [9]. The grey band in the upper panel represents possible lunar chemical compositions.