

**TESTING MODELS OF MOON ORIGIN: CONDENSATION OF IMPACT-VAPORISED BULK SILICATE EARTH MATERIAL.** M. I. Petaev<sup>1,2</sup>, S. B. Jacobsen<sup>1</sup>, and S. Huang<sup>1</sup>. <sup>1</sup>Department of Earth & Planetary Sciences, Harvard University, Cambridge MA 02138; <sup>2</sup>Harvard-Smithsonian CfA, Cambridge MA 02138.

**Introduction:** New isotopic data question the widely accepted model for the origin of the Earth-Moon system by the collision of a Mars-sized impactor with proto-Earth. Emerging new models invoke either additional post-impact processes for accounting for the available isotopic and geochemical evidence [1] or even new giant impact scenarios predicting most of the Moon to be derived from the Earth's mantle [2,3]. The starting point for examining such models is to consider the constraints provided by estimated chemical composition of the Moon's and Earth's mantles. Some sources [4,5] report similar compositions of both, except for differences in volatile elements due to their loss from the material that formed the Moon. Others [6] suggest that the Moon is somewhat enriched in the a refractory element component compared to the Earth. Here we use well established principles of chemical thermodynamics for calculating the composition of the Moon accreted from the vapor/magma circum-terrestrial disk formed by the putative Moon-forming giant impact.

**Model:** Following [7] we assume that a vapor cloud formed after giant impact experiences equilibrium condensation upon slow cooling in the pressure range of 10 mbars to 1 bar. Two compositions of the post-impact cloud are considered – Fa10 [7] and the bulk silicate Earth (BSE) [8]. In addition to equilibrium condensation we explicitly model effects of partial condensate isolation in a manner described in [9] and partial evaporation of condensates as they move from colder to hotter regions of the circum-terrestrial disk (a-la 'condensate rainout' of [7]). The results are compared with two different estimates of the bulk Moon composition [4, 5, 6]. The model also tracks isotopic compositions of the condensed and gaseous phases, with the results being reported in the accompanying abstract [10].

**Computational technique:** We used the 20 element (H, He, C, N, O, Na, Mg, Al, Si, P, S, Cl, K, Ca, Ti, Cr, Mn, Fe, Co, Ni) version of the GRAINS code [11] which thermodynamic database covers temperature range of 300 - 2500 K. Preliminary results for the systems of interest showed that only silicate melts are stable above ~2300K; therefore only data for molten oxides (Na<sub>2</sub>O, MgO, Al<sub>2</sub>O<sub>3</sub>, SiO<sub>2</sub>, K<sub>2</sub>O, CaO, TiO<sub>2</sub>, Cr<sub>2</sub>O<sub>3</sub>, MnO, FeO, CoO and NiO) were expanded to 5000 K using [12] or linear extrapolations of the Gibbs free energy expressions derived for 2000 - 2500 K. Thermodynamic properties of 59 gaseous species are

extrapolated in similar fashion, with the  $R^2$  exceeding 0.999 for condensed and 0.99999 for gaseous species. Tabulation of the relevant data from [12] is ongoing. The code considers two melt models – ideal and CMAS [13] assuming activity coefficients of Mg = Fe, Mn, Ni, Co, Si = Ti, Al = Cr, and Ca = Na, K. The models yield similar condensation curves but the condensation temperatures of ideal melts generally ~100 K lower. The diagrams reported below were calculated using ideal melt model.

**Results:** While some issues of the melt models and thermodynamic database still remain to be worked out, the modeling done so far produced some interesting results.

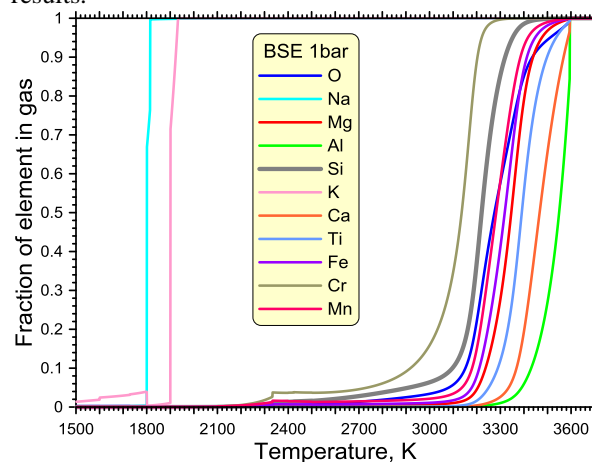


Fig. 1. Condensation of elements from the BSE vapor at 1 bar. The kinks on the curves below 2500 K results from minor inconsistencies in thermodynamic data between the melt and solid phases.

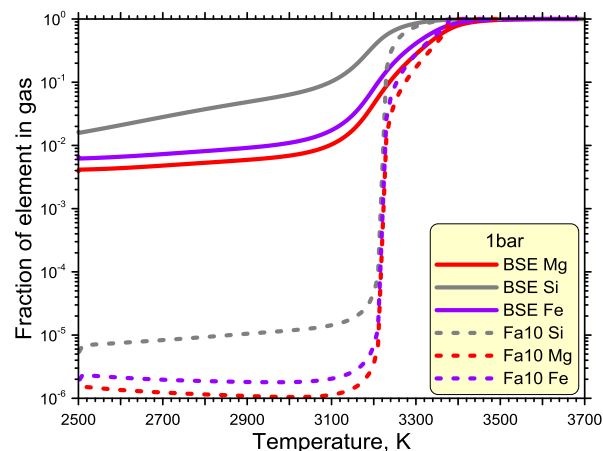


Fig. 2. Comparison of Fa10 and BSE condensation curves at 1 bar. Note a significant increase in Si, Mg, and Fe volatility over the BSE melt.

First, compared to the Fa10 composition, the addition of Ca, Al, Ti and alkalis to the vapor cloud (BSE) substantially expand the stability field of melt toward both higher and lower temperatures (Fig. 1) and significantly increases volatilities of Mg, Fe, and Si after melt condensation (Fig. 2), thus extending P-T conditions for isotopic fractionation.

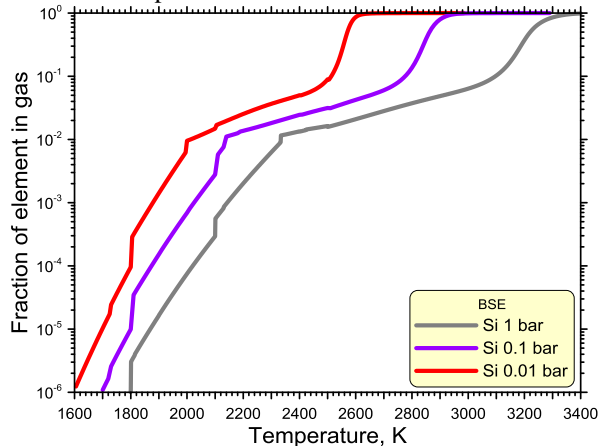


Fig. 3. Si condensation curves at different pressures.

Second, condensation of Si, the only element with expected significant isotope fractionation [10], is pressure dependent (Fig.3), suggestive of significant gradient in the vapor/melt ratio across the vapor-melt disk.

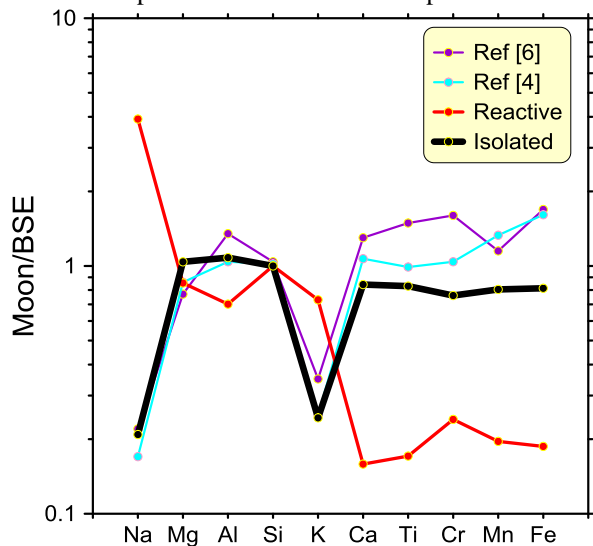


Fig. 4. Compositions of condensates formed in the BSE vapor disk at 1 bar relative to different estimates of the bulk Moon composition [4,6]. This model assumes gradual isolation of condensing material at the rate of 0.1% per K of cooling. As a result, there are two categories of condensate (see [9] for explanation) – (1) reactive condensate (red line) that continues to equilibrate with the ambient gas and (2) isolated condensate (black line) which no longer reacts with the gas perhaps due to physical isolation in larger objects.

Third, the condensation of volatiles like Na and K occurs at much lower temperatures than major elements (Fig. 1) when melt fraction in the condensate is fairly small. Moreover, an equilibrium condensation cannot account for the estimated elemental pattern of the Moon (Fig. 4), while some deviations from complete equilibrium due to the partial condensate isolation apparently can (Fig. 4).

**Conclusions:** Our calculations suggest that modeling condensation of the Fa10 material [11] is inadequate for understanding Moon formation in an impact-generated vapor-melt disk. Using a BSE composition for such a disk is a better approximation for condensation of the Moon from an impact-generated vapor. In such a model the Moon should accrete only a fraction (although large) of the material condensed before ~ 1500-1600 K. The residual gas and fine dust must be lost, perhaps via accretion on to the Earth. Alternatively, if the Moon is made primarily from vaporized impactor material, then the latter must be close to BSE in chemical and isotopic composition. This is consistent with our recent model for the inner solar system based on evidence from enstatite chondrites [14].

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