TESTING MODELS FOR THE ORIGIN OF THE MOON: STABLE ISOTOPIC FRACTIONATION.

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Introduction: Formation of the Moon is the center of many studies [1-5]. It has been known since the Apollo era that the Moon is depleted in volatile elements (Na, K) and possibly enriched in refractory elements, such as Ca and Al, compared to the Earth [e.g., 3]. Mass-dependent isotopic studies show that Moon and Earth may or may not have the same isotopic compositions [6-11]. We use chemical thermodynamics calculations 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 [1,2,4,5]. Specifically, we use established principles of thermodynamics to calculate the composition of the Moon formed as condensate from a silicate atmosphere with a bulk Earth composition (BSE); the results are presented in an accompanying abstract [12]. Here we discuss the mass-dependent isotopic effects of O, Mg, Si and Ca during condensation from a silicate atmosphere.

Method: 1. Two compositions of the vapor cloud are explored, Fa10 olivine [5] and a BSE composition [17]. In this abstract, we explore only equilibrium scenario. More sophisticated scenarios, such as fractional condensation, will be presented at the meeting. Details of the thermodynamic calculations are presented in [12]. **2.** Mass-Dependent Isotopic Fractionation Factors: To the best of our knowledge, there are no experimental data for equilibrium mass-dependent isotopic fractionation factors between condensed and vapor phases. However, such data are available in several first principles calculation studies [13-16], which calculated mass-dependent isotopic fractionation factors between common mantle minerals and atomic gases. While there are small isotopic fractionations among different mantle minerals as well as possibly between mantle minerals and basaltic melts, the isotopic fractionations among crystals and melts are much smaller than that between a condensed phase and atomic gases. Consequently, for simplicity, we assume 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 [13, 14, 16], while clinopyroxene data being used for Ca isotopes [15]. Our Si isotopic fractionation factor is slightly larger than that of [5].

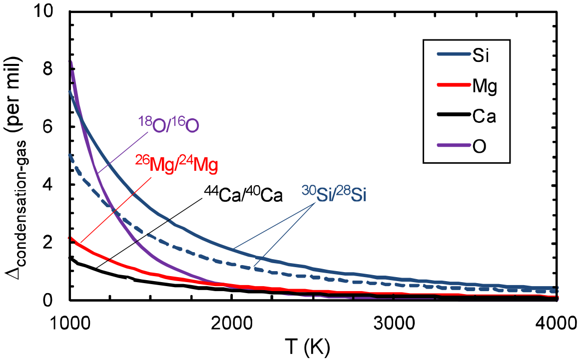

Fig. 1 Isotopic fractionation factors of O, Mg, Si and Ca between condensed and vapor phases in this study. The dashed blue line is the Si isotopic fractionation factor of [5].

Results and Discussion: The isotopic fractionations induced by equilibrium condensation are shown in Figs. 2-6. Si and Mg condense from the BSE vapor at higher temperatures (by ~100-200 K) than from the Fa10 vapor (Figs. 2, 3), reflecting the role of other major elements (e.g., Ca, Al) in expanding the stability field of a silicate melt.

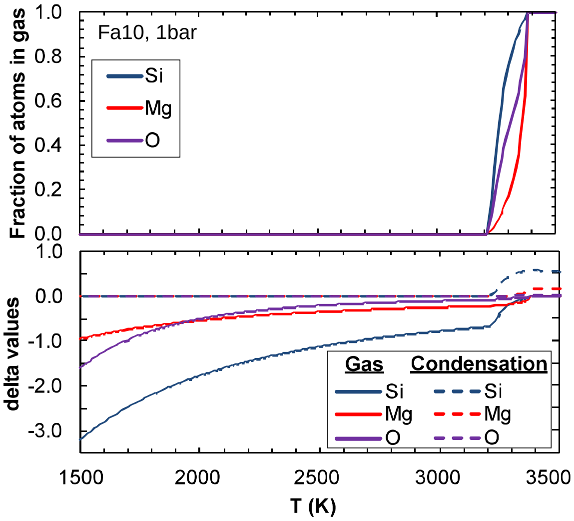

Fig. 2 Chemical and isotopic evolutions of condensed and vapor phases for the Fa10 olivine vapor at 1 bar. The top panel presents the atomic fractions of each elements in the vapor phase, and the bottom panel shows the delta values of each isotope in condensed (dashed lines) and vapor phases (solid lines).

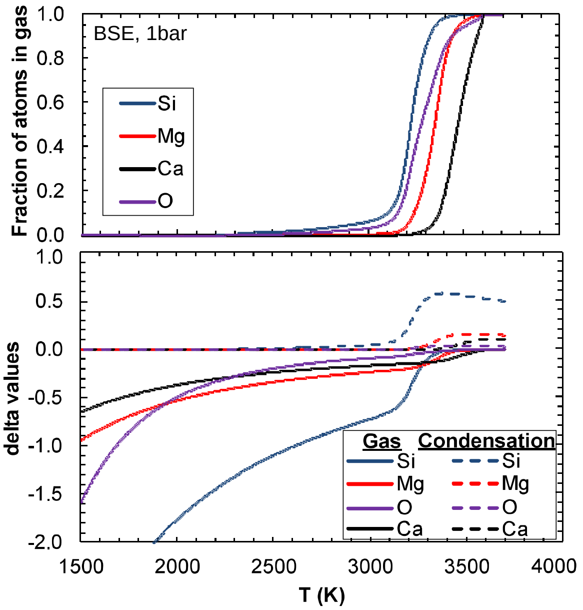

Fig. 3 Chemical and isotopic evolutions of condensed and vapor phases for the BSE vapor at 1 bar.

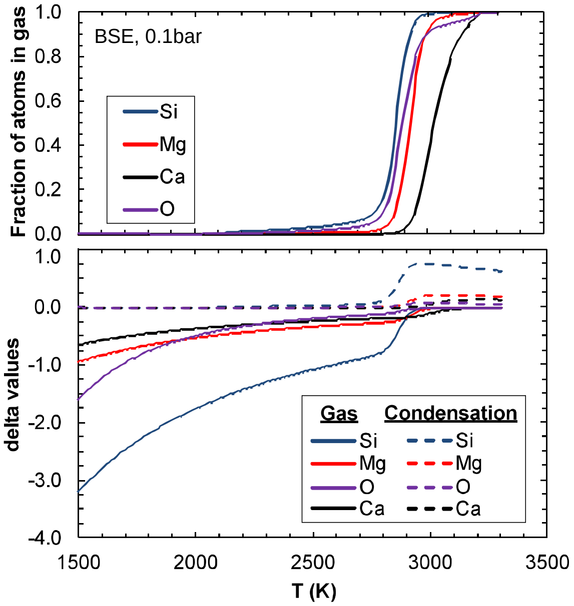

Fig. 4 Chemical and isotopic evolutions of condensed and vapor phases for the BSE vapor at 0.1 bar.

Large isotopic effects are observed only in vapor phase (Figs. 2-5) when the major components are condensed at lower temperatures. In condensed phase, only Si shows significant fractionation, with the isotopic effects of O, Mg and Ca being negligible (<0.1 per mil). Fig. 6 shows the relationship between Ca/Mg and $\delta^{30/28}$Si in the condensed phase. If the Moon has a $(Ca/Mg)_{BSE}$ of ~1.7 [3], then, according to our calculation, its $\delta^{30/28}$Si may be ~0.6. This conflicts with the Si isotopic measurement of lunar samples [e.g., 7]. This discrepancy requires either more sophisticated condensation models [12] or a re-evaluation of the lunar composition [3].

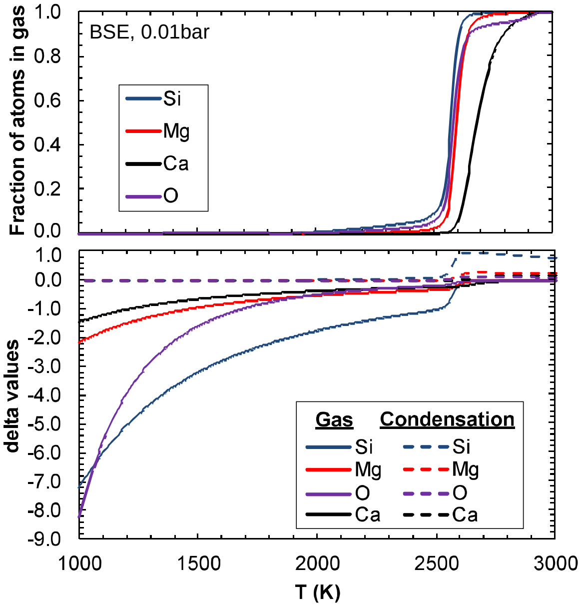

Fig. 5 Chemical and isotopic evolutions of condensed and vapor phases for the BSE vapor at 0.01 bar.

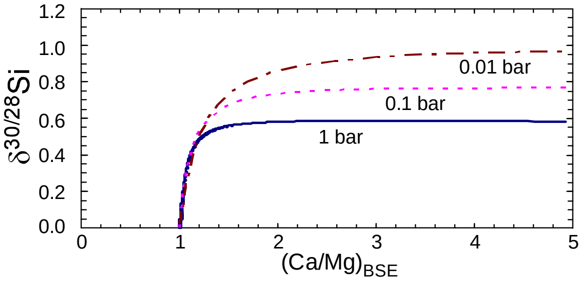

Fig. 6 Ca/Mg ratio (normalized to BSE) vs. $\delta^{30/28}$Si in condensed phase.

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