A NEW MODEL FOR LUNAR ORIGIN: EQUILIBRATION WITH EARTH BEYOND THE HOT SPIN STABILITY LIMIT.

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Introduction: The canonical giant impact model for lunar origin fails to explain key observables for the Moon [1], including the isotopic similarity between the Earth and Moon, the large mass of the Moon and the moderately volatile element depletion of the Moon. Various attempts have been made to resolve these issues with the giant impact model, most recently by using coupled physical-chemical models of the canonical disk [2], but none has yet provided a satisfactory explanation of the observations.

Here we present a new model for the formation of the Moon from the aftermath of a giant impact. High energy, high angular momentum giant impacts leave the Earth in a state that exceeds the hot spin stability limit (HSSL) in which the mantle atmosphere and disk (MAD) form a well-mixed continuous extended structure that reaches beyond the Roche limit [3]. The growing Moon equilibrates with the bulk silicate Earth (BSE) vapor and naturally generates the observed bulk lunar chemistry and isotopic similarity with Earth.

Cooling the post-impact MAD structure: The continuous majority-vapor structure cools rapidly by radiation from the outer regions of the structure. Silicate droplets form and fall inwards into higher pressure and temperature vapor. Droplets that fall within the Roche limit are vaporized; droplets that fall outside the limit can persist by accreting onto the growing Moon.

We have modeled the cooling of a post-impact MAD structure using a modified smooth particle hydrodynamics (SPH) code. The particle entropy and radial mass distribution are adjusted by algorithms that approximate radiative cooling and convective mixing while conserving angular momentum. At each time step, condensing liquid beyond Roche is removed from the calculation and tracked as the growing moon.

The Moon is formed rapidly. In an example case (Figs. 1 and 2), the moon forms in 10 to 20 yrs within 10's bars of BSE vapor. The structure contracts within the Roche limit in ~50 yrs.

Lunar chemistry: The MAD structure is being driven to mix rapidly by the torrential rain of droplets and thermal convection. The mixing timescale is on the order of weeks, much shorter than the lunar formation timescale. The Moon condenses from, and equilibrates with, a well mixed BSE vapor, naturally explaining the isotopic similarity between the Earth and the Moon.

We have used a Gibbs free energy minimization code to calculate the phase diagram of BSE vapor at the pressures and temperatures relevant to lunar formation [4]. We calculate the composition of the Moon formed from the MAD structure.

Droplets that condense at the surface of the structure acquire the refractory element composition of the bulk vapor, but the equilibrium composition contains a lower abundance of moderately volatile elements than observed in the moon. As the droplets fall, they equilibrate both chemically and thermally with the surrounding gas. If the droplets remain small, they evaporate quickly, but larger moonlets can survive in the gas much longer than the timescale of lunar formation due to the large latent heat of vaporization of silicates. As silica is the first major component to begin to vaporize, the moonlets equilibrate at the temperature dictated by silica vaporization (Fig. 3).

The moonlets acquire the equilibrium composition of the condensate at the pressure of gas in the structure and a temperature dictated by silica vaporization. The predicted composition of the condensate at these P-T conditions is in excellent agreement with the bulk lunar chemistry including the magnitude of the depletion in moderately volatile elements and other trace elements (Fig. 4). Little isotopic fractionation between the Earth and Moon would be expected [5].

As cooling continues, the radius of the structure contracts, leaving the Moon surrounded by its own gravitationally bound silicate atmosphere (Fig. 1). Volatiles remain in the vapor structure bound to the Earth. The Earth continues to contract and cool, eventually falling below the HSSL and reaching a corotating state with a silicate atmosphere and mostly liquid mantle. During the Moon's tidal evolution, angular momentum is removed from the Earth-Moon system. A new tidal evolution model can explain both the angular momentum removal and lunar inclination [6].

Conclusions: Our model for the formation of the Moon by equilibration with the BSE after a high energy, high angular momentum giant impact predicts the observed isotopic and elemental composition of the Moon. The criteria for a successful Moon forming impact shifts from a specific set of impact parameters to a range of impacts that produce the required post-impact state beyond the hot spin stability limit.

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References: [1] Melosh, H. (2014) *Proc. R. Soc.* 372, 20130168. [2] Canup R. M. et al. (2015) *Nature Geosci.* 8, 918-921. [3] Lock S. J. and Stewart S. T. (2016) *LPSC XLVII.* [4] Petaev M. I. et al. (2016)

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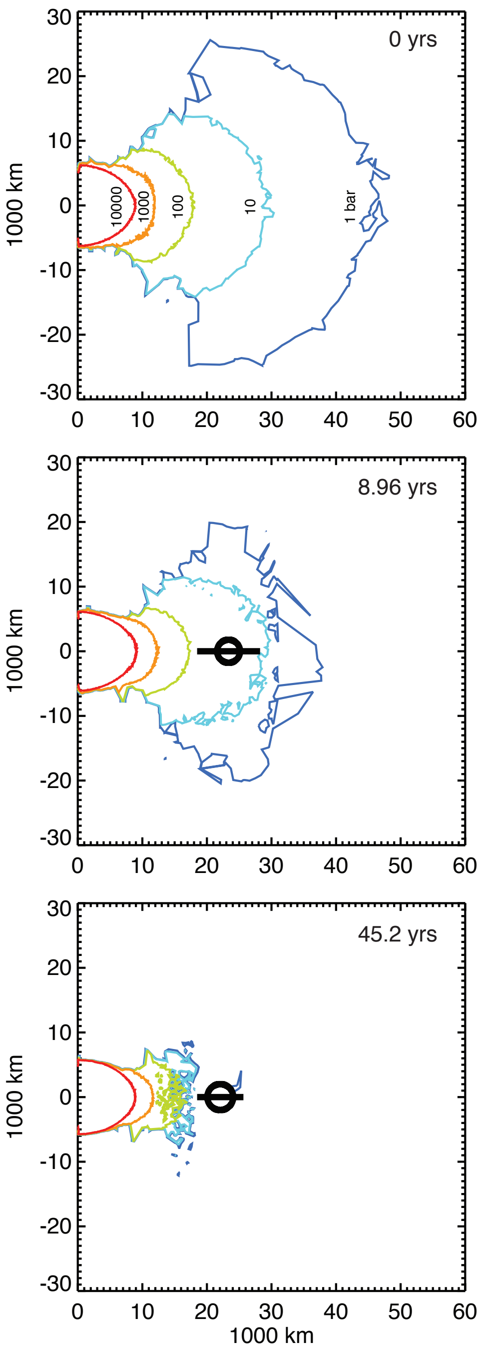

Figure 1: Snapshots from cooling model of the post-impact vapor structure around the Earth. View is perpendicular to the rotation axis showing pressure contours (labeled). Moon (to scale) is shown in black with the uncertainty in orbital radius indicated by horizontal bar.

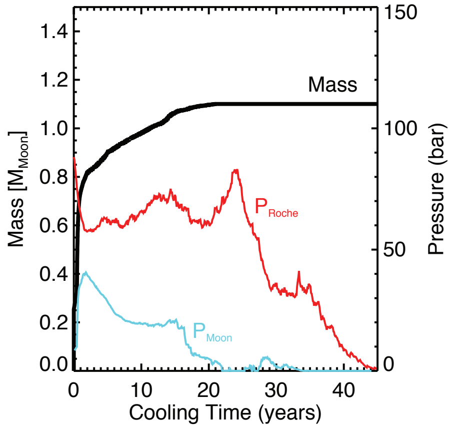

Figure 2: Mass of the Moon (black) and the pressures at the Roche limit (red) and the Moon's location (blue) as a function of time.

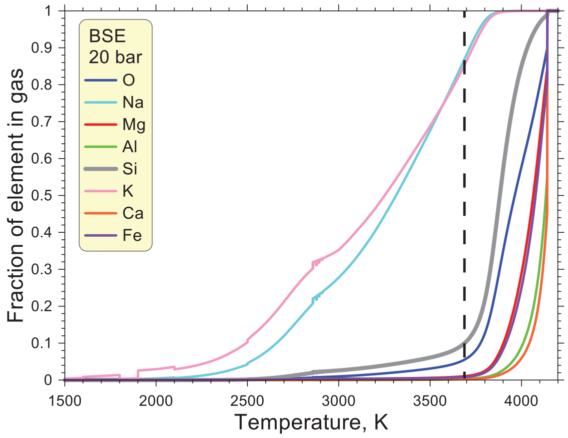

Figure 3: Selected condensation curves at 20 bar. Vertical line indicates the onset of significant silica vaporization (~10% Si in vapor).

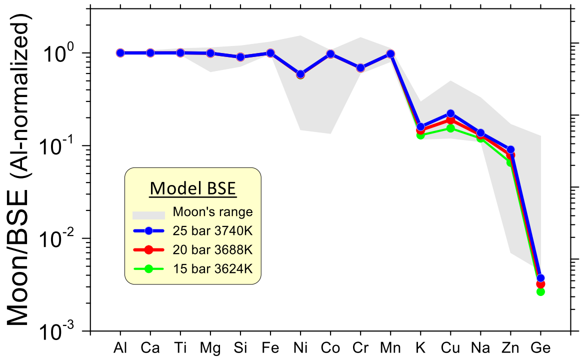

Figure 4: Predicted composition of the Moon from our model. Chemical equilibration occurs at a pressure determined by the vapor mass in the disk (Fig. 2) and temperature set by ~10% vaporization of silica (Fig. 3). Grey band indicates range of estimates for bulk lunar composition.