

**CHEMICAL FRACTIONATION AFTER THE MOON-FORMING GIANT IMPACT.** K. Pahlevan and D. J. Stevenson, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125 (kaveh@gps.caltech.edu)

**Introduction:** The Moon is generally thought to have formed from a circumterrestrial disk generated by the impact of a Mars-sized body onto a nearly-formed Earth [1]. The gravitational energy released in such an event is sufficient to completely melt and partially vaporize the Earth and lunar-forming material. This fluid phase of the evolution is not well understood, but may have delayed lunar accretion by  $\sim 10^3$  years [2].

Despite widespread isotopic heterogeneity in the inner Solar System, the Earth and Moon are identical with respect to oxygen [3] and tungsten isotopes [4]. Because impact simulations derive most of the lunar material from the impactor [5,6], the “terrestrial” character of lunar isotopes has been used to argue for an episode of isotopic equilibration of the proto-lunar disk and post-impact Earth through turbulent exchange while the system is in a fluid state [7]. However, such a scenario prompts the question of why *chemical* differences exist between the silicate Earth and Moon. Here, we ask whether liquid-vapor fractionation during the post-impact high-temperature era could have evolved chemical differences between the Earth and the proto-lunar disk, even as it eliminated isotopic heterogeneity.

One consequence of the equilibration hypothesis is that liquid-vapor equilibrium played a central role in lunar formation. At sufficiently high temperatures, the isotopic fractionation between co-existing phases approaches zero [8]. However, because silicate mantles are multi-component systems, the chemical composition of a silicate liquid and its co-existing vapor will, in general, be different. This behavior of high temperature equilibrium – of similar isotopic but different chemical composition of co-existing phases – makes this process a prime candidate for explaining isotopic similarities and chemical differences between the silicate Earth and Moon. Here, we are testing the hypothesis that the Moon acquired its major-element composition by being composed of a sample that is vapor-rich.

There are several differences between the composition of the silicate Earth and Moon that may serve to constrain the role of liquid-vapor fractionation during lunar formation. Here, we focus on the elevated Fe/Mg ratio of the lunar mantle relative to Earth’s, a feature inferred on the basis of petrologic and geophysical constraints [9]. We choose this feature for several reasons. First, both iron and magnesium are major elements in silicate mantles, and their lunar abundances are therefore constrained – even in unsampled regions – by geophysical measurements. Second,

these oxides have significantly different vaporization behavior, FeO being much more volatile than MgO [10], making the Fe/Mg ratio a sensitive tracer of even small degrees of liquid-vapor separation. Third, the behavior of trace elements is generally passive – it depends on the behavior of the major elements. Finally, thermodynamic data for major element liquids exist at the temperatures of relevance ( $T > 4,000$  K). For the purposes of these calculations, we take the Fe/Fe+Mg ratio of terrestrial silicates to be 0.1 [11] and the elevated (but more uncertain) lunar value to be about 0.15-0.2 [9].

**Model Assumptions:** In the context of the equilibration hypothesis, there are multiple sites for chemical fractionation to take place: within the post-giant-impact Earth or – since the Moon forms from the outermost disk material – within the melt-vapor proto-lunar disk. Here, for simplicity, we assume that the composition at the top of the Earth’s silicate vapor atmosphere is acquired by the proto-lunar disk without further fractionation and expressed in the lunar bulk composition. Because the vertical component of gravity, the driving force for phase separation, is roughly one order of magnitude greater on Earth than in the proto-lunar disk, such a scenario of chemical fractionation on the Earth – but not the disk – is plausible. For the purposes of these calculations, we approximate the silicate mantle of Earth as an ideal solution of  $(\text{Fe,Mg})_2\text{SiO}_4$ . We assume that the vapor in equilibrium with an olivine liquid is stoichiometric olivine, in accordance with experiments [12], the only compositional degree of freedom being the Fe/Mg ratio.

**Results:** There are two ways in which liquid-vapor fractionation may have taken place on the post giant-impact Earth, and they depend on the state of the Earth in the afterglow of the giant impact.

*Settled Earth.* The partially vaporized Earth may be in a “settled” state, with a magma ocean, a smooth liquid-vapor interface, and an overlying silicate vapor atmosphere (which, through condensation, transitions continuously into a steam atmosphere). In such a state, the ocean and atmosphere are separately convecting, with the entropy difference between the two isentropic columns dictated by thermodynamics (and the cooling history). Because only a small fraction of the Earth vaporizes after the giant impact, the major-element composition of the residual liquid in such a model remains essentially unchanged by vaporization. We have calculated the composition of the vapor in equilibrium with the terrestrial magma ocean, assuming the

vapor consists of an ideal gas of simple molecules formed when silicates vaporize:  $\text{SiO}_2$ ,  $\text{SiO}$ ,  $\text{MgO}$ ,  $\text{Mg}$ ,  $\text{FeO}$ ,  $\text{Fe}$ , and  $\text{O}_2$ . The thermodynamic data come from standard sources [13]. We can see from Figure 1 that if the lunar disk acquired its chemical composition from an atmosphere above a settled magma ocean, the temperature of last equilibration must have been 4,500-4,800 K in order to yield the elevated lunar Fe/Mg ratio.

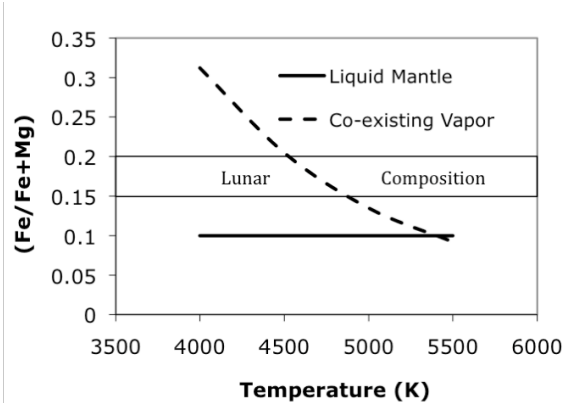


Figure 1 – Vapor composition in equilibrium with the terrestrial magma ocean.

*Unsettled Earth.* Because the Earth is vigorously convecting while cooling during the afterglow, it may remain in an “unsettled” state. In such a case, one convective column – and hence one value of entropy – nominally characterizes the silicate Earth from deep regions where only liquid is present through the top of the silicate vapor atmosphere. In the absence of rain-out, the composition at the top of the atmosphere reflects that of the well-mixed magma ocean. However, adiabatic ascent of vapor parcels leads to condensation, with rain-out of the liquid resulting in parcel compositions distinct from the bulk silicate Earth.

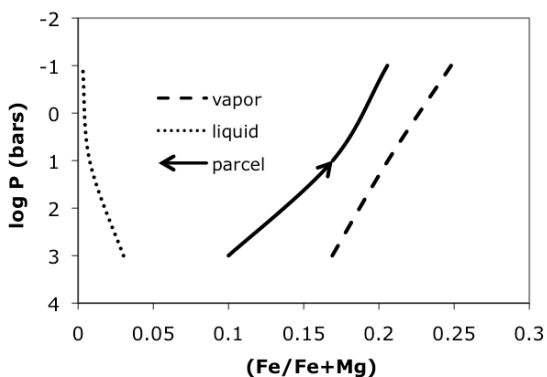


Figure 2 – Distillation by rain-out of condensates (fractional condensation) of a parcel on an unsettled Earth.

Plotted in Figure 2 is the result of an example distillation calculation with an initial parcel entropy of  $15k_B/\text{atom}$ , which corresponds to a temperature of 3360 K and a vapor fraction of 0.44 at the reference pressure of 1 bar. We can see that the removal of Mg-rich droplets over four orders of magnitude of pressure variation in an isentropic atmosphere can evolve a  $\sim 2x$  enhancement in the Fe/Mg ratio. The actual value of the entropy of the convecting silicate Earth will depend on the cooling history, starting high when the Earth first becomes fully convective, sweeping to low values as the Earth gradually cools.

**Conclusions:** The silicate Earth-Moon system is isotopically homogeneous, but chemically distinct. Liquid-vapor fractionation in the time after the giant impact can generate parcels in the Earth’s atmosphere that have the lunar composition in terms of isotopic composition and one major-element chemical tracer (Fe/Mg). Liquid-vapor fractionation, if it was responsible for generating chemical differences in the silicate Earth-Moon system, would not have been restricted to the Fe/Mg ratio, but would have involved every other element and isotope ratio. Such a one-stage differentiation model does *not* explain the lunar volatile depletion [14] and the possible enhancement of  $\text{CaO}$ ,  $\text{Al}_2\text{O}_3$  of the Moon relative to Earth mantle [15]. Nevertheless, the scenario outlined here suggests that the lunar material represents a fractionated snapshot of the Earth’s mantle at the time of the giant impact. The temperatures of equilibration inferred here via Fe/Mg thermometry may be tested via high-precision isotopic measurements.

**References:** [1] Canup R. M. and Asphaug E. (2001) *Nature*, 412, 708-712. [2] Thompson, C. and Stevenson, D. (1988) *Ap.J.* 333, 452-481. [3] Wiechert U. et al. (2001) *Science*, 294, 345-348. [4] Touboul M. et al. (2007) *Nature*, 450, 1206-1209. [5] Canup, R. M. (2004) *Icarus*, 168, 433-456. [6] Canup, R. M. (2008) *Icarus*, 196, 518-538. [7] Pahlevan, K. and Stevenson, D. (2007) *EPSL*, 262, 438-449. [8] Urey, H.G. (1947) *J. Chem. Soc.* 1, 562-581. [9] Mueller, S. et al. (1988) *J. Geophys. Res.* 93, 6338-6352. [10] Mysen, G. and Kushiro, I. (1988) *Am. Min.* 73, 1-19. [11] Jones, J. H. and Palme, H. (2000) *Origin of the Earth and Moon*, pp. 197 [12] Nagahara, H. et al. (1994) *GCA*, 58, 1951-1963. [13] Chase, M.W. et al. (1985) *J. Phys. Chem. Ref. Data*, 14, 1, 1-1856. [14] Ringwood, A.E. (1979) *Origin of the Earth and Moon*. Springer-Verlag. [15] Taylor, S.R. et al. (2006) *GCA* 70 5904-5918.