

EQUILIBRATION 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 the forming Earth [1]. Both the impact shock-heating, and the viscous self-heating of the disk, liberate enough energy to completely melt and partially vaporize the orbiting, lunar-forming material. This dynamical continuum phase is not well understood, but may have delayed lunar accretion for a period of up to $\sim 10^3$ years [2].

Despite widespread oxygen isotope heterogeneity in the Solar System, the Earth and Moon are identical with respect to oxygen isotopes [3]. Because impact simulations derive most of the lunar material from the impactor [4], the “terrestrial” character of oxygen isotopes in lunar samples has been used to argue for chemical equilibration of the proto-lunar disk and post-impact Earth, mediated by exchange with a silicate-vapor atmosphere connecting the terrestrial magma ocean and the melt-vapor disk [5]. Here we discuss recent isotopic evidence in support of this hypothesis, as well as some of the chemical questions it raises.

Tungsten Isotopes: Tungsten-182 is generated by the decay of the short-lived nuclide Hafnium-182 ($T_{1/2} = 9$ Myrs). Because W is siderophile and Hf lithophile, the isotopic composition of W is a chronometer for early Solar System metal-silicate equilibration, a process that is sometimes related to core-formation and planetary accretion. The tungsten isotopic composition of the Earth’s mantle is determined by the timing of core-formation in pre-cursor bodies, the rate of Earth accretion, the degree of W partitioning into core metal, and the amount of metal-silicate equilibration during core-formation. Consequently, the measured radiogenic isotopic composition of tungsten in Earth’s mantle [7,8] is a signature that reflects both the timing and character of terrestrial core-formation processes.

The determination of the tungsten isotopic composition of lunar reservoirs has been hampered by cosmogenic production and burnout of W isotopes at the lunar surface. A recent measurement of lunar metals [9], largely impervious to cosmic-ray effects, finds that the W isotopic composition of lunar mantle reservoirs are: (1) uniform and (2) indistinguishable from the terrestrial mantle. While the former observation tells us that the giant impact occurred after Hf-182 was effectively extinct, the latter raises the possibility that the lunar material inherited the tungsten isotopic composition of Earth mantle through turbulent mixing.

Impact simulations that are successful in generating a suitable proto-lunar disk typically contain a few percent metal – derived from the impactor’s core – into orbit [4]. The upper limit on the mass of the lunar core derived from geophysical constraints is also a few percent [9]. Because early-differentiated metal has a tungsten isotopic composition complementary to silicates, the metal injected into orbit very likely had a tungsten isotopic composition distinct from Earth mantle. Hence, an additional constraint derived from tungsten isotopes is: if metal-silicate equilibration occurred during lunar core formation [10], then tungsten inheritance from Earth mantle requires both the lunar metal and the silicates to have participated in the equilibration process.

We have evidence from the isotopic composition of oxygen, silicon [6], and tungsten that tracers may have become well-mixed in the aftermath of the giant impact. Here, we briefly turn to a discussion of the consequences of equilibration for lunar chemistry.

Chemical Constraints: Chemical constraints on post giant-impact processes are difficult to assess for several reasons. First, because the Moon is a highly differentiated object and may also be laterally heterogeneous, determining bulk lunar abundances from samples is not a trivial task. Second, the thermodynamic database for the behavior of elements in the high-temperature silicate melt-vapor system is, at present, incomplete. Finally, the dynamics (the vigor of turbulent mixing, etc.), which depend in part on the chemistry, are uncertain. The approach we take here is to assume that isotopic Earth-Moon similarities do indeed require an episode of equilibration. The question we then ask is: could differences in chemical composition between the Earth and Moon have arisen through liquid/vapor fractionation?

Liquid-Vapor Fractionation: There are two aspects to this question. First, from a thermodynamics perspective, there is a strong, temperature-dependent elemental partitioning between the liquid and vapor. However, liquid-vapor fractionation can only give rise to chemically distinct reservoirs if the system undergoes phase separation through bubble ascent or droplet settling. Although both of these processes may have operated, they may be distinguished by leaving behind distinct chemical signatures. In particular, in an isentropic column, bubble ascent through a magma will occur at higher temperatures than liquid rain-out, and

the problem may be simplified by the fact that convective columns in this system are nearly at the same entropy [2]. Irrespective of the details, it may be significant that 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. Given that maximally-sized droplets are marginally unstable to gravitational settling in the lunar disk [2], this difference may be a decisive factor determining the extent of phase separation. Here, we focus on two chemical constraints on lunar composition that may have a bearing on the extent of liquid-vapor fractionation following the giant impact.

FeO/MgO Ratio: The FeO/MgO ratio in lunar basalts is higher than terrestrial basalts [11], which implies that the mantle source region is similarly enriched in FeO. Because iron is a major element, its bulk lunar abundance also influences geophysical measurements, namely, the seismic dataset and the density and moment of inertia constraints [9]. This difference in FeO abundance may arise during chemical equilibration because FeO is significantly more volatile than MgO in silicate melts [12]. We will present the result of calculations that demonstrate the conditions under which thermodynamics and turbulent mixing can generate this silicate Earth-Moon difference.

Rare-Earth Elements: The abundance patterns observed in lunar samples are the product of two sets of processes: (1) crystal-liquid equilibria, which have operated on the lunar material during igneous differentiation, and (2) liquid/vapor equilibria, which may have acted on the lunar material during lunar formation. Because the silicate Moon has undergone a series of differentiation events, all accessible samples carry the imprint of petrologic processes. For this reason, in order to study liquid/vapor fractionation processes relevant to lunar formation, it would be ideal to select a suite of elements whose behavior during high-temperature formation processes is distinctly different from subsequent igneous processes. The rare-earth elements are one such example.

Aside from pervasive Eu anomalies, which can be explained by crystal/liquid fractionation, there are no other REE anomalies reported in lunar samples. In contrast with their behavior during igneous processes, the REE's do not display a monotonic pattern with increasing atomic number during liquid/vapor fractionation. In fact, the volatility of the REE's depends not only on the properties of the REE's, but also on the chemical environment (i.e. the oxygen fugacity), which is determined by the major elements. Unlike the temperatures relevant to condensation in the solar nebula

($T < 2000$ K), the thermodynamic database for the behavior of REE oxides at temperatures relevant to Earth-Moon origin (2000-4000 K) is much more incomplete. Completing such a database may enable a critical test of the equilibration hypothesis by placing well-defined constraints on the chemical conditions and amount of liquid/vapor fractionation that can be tolerated prior to lunar formation.

Conclusions: We do not yet have a full dynamical and chemical account of the events that happened between the giant impact and lunar accretion. However, geochemical signatures are capable of informing us of the processes operating during this earliest period of Earth-Moon history. Several isotopic tracers provide evidence for mixing during this period. However, a satisfactory scenario of equilibration must have well-defined chemical and dynamical conditions, be able to predict whether a particular element did or did not equilibrate, and account for both Earth-Moon similarities and differences. Such a scenario can inform us on the extent to which the Moon represents a geochemical archive of the state of the Earth just after formation.

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] Canup, R. M. (2004) *Icarus*, 168, 433-456. [5] Pahlevan, K. and Stevenson, D. (2007) *EPSL*, 262, 438-449. [6] Georg, R.B. et al. (2007) *Nature*, 447, 1102-1106. [7] Yin, Q. et al. (2002) *Nature*, 418, 949-952. [8] Kleine, T. et al. (2002) *Nature*, 418, 952-955. [9] Hood L. L. and Zuber M.T. (2000) *Origin of the Earth and Moon*, pp. 397 [10] Walter M. J. et al. (2000) *Origin of the Earth and Moon*, pp. 265 [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.