UNSTRATIFIED MIXING AFTER THE MOON-FORMING GIANT IMPACT. K. Pahlevan and D. J. Stevenson, Department of Geology & Geophysics, Yale University, New Haven, CT (kaveh.pahlevan@yale.edu), Division of Geological and Planetary Sciences, Caltech, Pasadena, CA (djs@gps.caltech.edu).

Introduction: The Moon is generally thought to have formed from a circumterrestrial disk generated by a giant impact between the growing Earth and a Mars-sized planet [1]. The gravitational energy released in such an event is sufficient to completely melt and partially vaporize the nascent Earth-Moon system, and to keep the system in a hot, fluid state for ~10^3 years before radiative cooling leads to crystallization [2]. However, due to an incomplete understanding of processes occurring during this fluid phase, we do not yet have a predictive theory of lunar origin. Since the chemical and isotopic signatures of the giant impact may have been imprinted during this period, the giant impact hypothesis cannot be tested cosmochemically without an articulation of the compositional consequences of processes acting during this earliest period of lunar history.

Turbulent Mixing: The ubiquitous prediction from impact simulations that the proto-lunar disk was sourced from the mantle of the impacting planet [3,4] does not explain the “terrestrial” isotopic character of the lunar material [5,6,7] unless the terrestrial and lunar fluids were homogenized via turbulent convection into a single, uniform reservoir in the ~10^3 years after the giant impact but before the onset of crystallization [8]. The turbulent mixing hypothesis is unique among giant impact scenarios in that it derives the proto-lunar material from the terrestrial mantle. Furthermore, this scenario is attractive because it has testable consequences.

Unstratified Mixing: Here, we outline some of the consequences of a particular variant of the turbulent mixing hypothesis, namely, that of unstratified mixing between the terrestrial magma ocean and the melt-vapor proto-lunar disk [9]. In such a scenario, a single isentropic column characterizes the silicate Earth from deep levels where only liquid is present to the upper regions of the silicate vapor atmosphere where heat and entropy are radiated to space, and where turbulent exchange with the proto-lunar disk takes place. The disk in contact with such an atmosphere is similarly characterized by an isentropic structure. This scenario has the property that the rate of mixing is determined by macroscopic turbulence rather than molecular processes [10], and it makes predictions that can be tested by measuring the lunar chemical and isotopic composition. Here, we articulate some of these predictions.

Refractory Tracers. In an unstratified mixing scenario, turbulent exchange between the silicate Earth and proto-lunar disk involves not only the vapor phase, but also the liquid from the underlying magma ocean that is advected into the vapor atmosphere where it takes the form of droplets suspended via convection. Hence, even elements that quantitatively partition into the liquid (“refractory tracers”) can become isotopically homogenized in the silicate Earth-Moon system through the coupling of the droplets to the exchanging vapor. Such a scenario therefore predicts a high-level of mass-independent isotopic homogeneity in the Earth-Moon system for all elements irrespective of volatility. An isotopic homogeneity in the silicate Earth-Moon system would, for example, be expected for calcium isotopes, as observed [11]. However, such an observation is relevant to the processes of lunar origin only to the extent that such homogeneity is set against a background isotopic heterogeneity in the Solar System. This may be the case for the isotopes of the element titanium [12]. In addition to isotopic tracers, the relative abundances of the refractory elements will, in this scenario, be homogenized between the silicate Earth and Moon. Therefore, any pre-existing silicate differentiation on the proto-Earth and impactor inherited by the proto-lunar disk through the giant impact may be erased through post-impact processing, overcoming a potential problem with the giant impact hypothesis [13].

Chemical Fractionation. The chemical consequences of unstratified mixing can also be readily articulated. In such a scenario, the chemical composition of a parcel of the terrestrial magma ocean is advected into the atmosphere – in the form of volatile-rich vapor and complementary droplets – and is exchanged with analogous melt-vapor parcels in the proto-lunar disk. In the absence of phase separation, such an exchange process ultimately erases both the isotopic and chemical memory of the impactor from the proto-lunar disk and results in a silicate Moon that is isochemical with the terrestrial mantle. Because the chemical composition of a multi-component silicate liquid and its co-existing vapor will, in equilibrium, be distinctly different, phase separation during the exchange episode – either in the silicate vapor atmosphere of the Earth or the melt-vapor lunar disk – can lead to chemical (and small mass-dependent isotopic) differences between the silicate Earth and Moon. Indeed, observed chemical differences between the silicate Earth and Moon, for example, the lunar volatile element depletion [14] signals an important role for phase separation during the processes of lunar formation. However, the extent to which phase separation (“rainout”) occurs depends
on the competing effects of gravitational forces on liquid droplets driving the separation versus the vigorous convective motions that tend to keep the droplets suspended. Furthermore, because the extent of phase separation depends on the size-distribution of droplets, a robust prediction for the degree of liquid-vapor fractionation requires detailed microphysical modeling of silicate clouds. Hence, one consequence of this scenario is that the chemical composition that was inherited by the silicate Moon from the silicate Earth was determined—in part—by cloud physics. Despite the absence of a detailed microphysical model, the degree of phase separation can be constrained by precise measurements of isotopic ratios that are also sensitive to liquid-vapor separation.

Isotopic Fractionation. Ever since Apollo, and especially in the last several years, isotopes have been used to shed light on the lunar formation process. Here we discuss the consequences of unstratified mixing for the isotopic composition of the major elements. In the absence of phase separation, even the isotopic composition of elements that partially vaporize should be homogeneous in the silicate Earth-Moon system. However, it has been shown that the silicon isotope composition of a silicate liquid and co-existing vapor in equilibrium are distinctly different, even at the temperatures encountered in the post-giant-impact environment [9]. Therefore, small, mass-dependent differences in the silicate Earth-Moon system may have evolved depending on the extent to which the liquid droplets separated from the vapor during the era of turbulent ejection. I will present results that extend the calculations of isotopic fractionation to the elements magnesium, iron and oxygen and will use these results to make predictions for the expected degree of isotopic similarity between silicate Earth and Moon.

Lunar Bulk Composition. Because both the chemical and the isotopic composition of the parcels inherited by the lunar fluid are determined by the same process of liquid rainout, chemical and isotopic differences between the silicate Earth and Moon should be concomitant. Hence, precise measurements of silicon isotopes in lunar and terrestrial samples can constrain the degree of liquid-vapor separation that occurred during formation and therefore set constraints on the lunar bulk composition. This argument has been quantified for fractionation in one of the settings relevant to this problem: if the widely postulated ~2x enhancement in the FeO/MgO ratio of the silicate Moon relative to Earth mantle arose through the process of rainout solely in the silicate vapor atmosphere of the Earth, then the silicate Moon is predicted to display a ~0.14 per mil offset its $^{30}\text{Si}/^{28}\text{Si}$ ratio relative to the silicate Earth [9]. This is not observed [7]. In fact, no silicon isotope difference between the silicate Earth and Moon has been observed, providing no isotopic evidence for liquid-vapor separation during lunar formation.

There are several ways to reconcile the widely inferred difference in the FeO/MgO ratio of the silicate Earth and Moon [16] with the observed identity in the silicon isotope composition of these two reservoirs [7]. First, it is possible that a two-stage model, also involving fractionation in the proto-lunar disk, may yield a different relationship between isotopic and chemical differences in the silicate Earth-Moon system than the one-stage model considered thus far [9]. Second, since the lunar seismic data date back to Apollo, seismic inversions for the lunar composition are mostly sensitive to the lunar nearside [16]. Since the Moon is known to exhibit lateral heterogeneity, the bulk silicate Moon may have a composition that is different from seismic inferences and nearly isochemical with the terrestrial mantle, a viewpoint that has been defended by some petrologists for 25 years [15]. Finally, the simple, two-component thermodynamic model used to approximate terrestrial and lunar silicates may not capture the partial vaporization behavior of silicon during the turbulent mixing era, and more realistic thermodynamic models of high temperature magmas ($T = 2,500$-$3,500 \text{ K}$) may be required to make robust predictions for the signatures of lunar formation.

Conclusions: In the context of the giant impact hypothesis, a high-level of mass-independent isotopic homogeneity can evolve for isotopic tracers of all elements irrespective of their volatility. Small, mass-dependent differences can evolve in the Earth-Moon system for elements that undergo partial vaporization, but only to the extent that there was liquid-vapor separation during the $\sim 10^3 \text{ year}$ fluid phase of the evolution. The depletion of volatile elements in the Moon is still unexplained and is a goal for future research.