THE OXYGEN ISOTOPE SIMILARITY BETWEEN THE EARTH AND MOON – SOURCE REGION OR FORMATION PROCESS? Kaveh Pahlevan and David J. Stevenson, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125. (kaveh@gps.caltech.edu).

Introduction: The oxygen isotope composition of lunar samples is indistinguishable from the terrestrial fractionation line on the three-isotope plot within analytical uncertainties [1]. By contrast, the oxygen isotope composition of Mars, as represented by the SNC meteorites, falls on a fractionation line clearly distinct from that of the Earth-Moon system (figure 1).

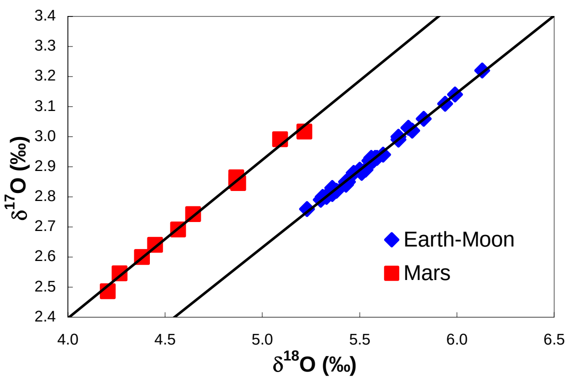

Figure 1. Oxygen isotopes for Earth-Moon system and Mars. Data from [1].

The standard interpretation of these observations is that they reflect an isotopic similarity between the moon-forming impactor and the proto-Earth. Here we argue that such a scenario is unlikely and instead propose that mixing between the Earth and the circumterrestrial disk in the aftermath of the giant impact would homogenize the terrestrial and proto-lunar material, reducing the difference in oxygen isotope composition.

The Problem: In the context of the giant impact scenario [2], the identical oxygen isotopes of the Earth and Moon (to within a few percent of the difference between Earth and Mars, [1]) have been interpreted to mean that the impacting protoplanet and the forming Earth were compositionally similar with respect to their oxygen isotopes. Such an interpretation places severe constraints on the initial composition of the impactor. One reason is that the impact simulations which are successful in forming the Moon suggest that most (~80%) of the proto-lunar material is derived from the impactor, not the Earth [3]. In this case, even small isotopic differences between the two colliding bodies should have left observable signatures between the two resulting bodies because the impactor-derived lunar material escapes the diluting effects of mixing with the largest reservoir in the system, the Earth.

There is a problem with this interpretation that derives from our ideas of how the terrestrial planets accumulate from the protoplanetary disk. The standard interpretation of the oxygen isotope data assumes that the material forming the proto-Earth and the impactor were derived from the same source region. If we assume that the terrestrial planet region exhibited oxygen isotope variations, as inferred for the asteroid belt by meteorite studies [4], then the oxygen isotope compositions reflect the source regions of the inner solar system which were sampled by each planet during the accumulation process.

The process of runaway growth in the preplanetary disk occurs very rapidly, on ~10^5-10^6 year timescales. In this process, embryos rapidly accrete all of the material in their feeding zone, as they grow to isolation at about lunar-to-Mars mass. The feeding zones are typically only ~0.01 AU wide [5], and hence planetary embryos up to about Mars size – the size inferred for the impacting protoplanet – tend to record the oxygen isotope signature of their immediate vicinity in the disk. By contrast, the formation of Earth and Venus requires an extended stage of planetary accumulation characterized by giant impacts, a stage with a very different mode of sampling compared to that of the precursor embryos.

In the last stage of growth, planetary embryos are scattered away from their places of birth. Thus, this stage of the accumulation process is accompanied by significant radial mixing. The planets that undergo giant impacts in this last stage sample material from a broad region of the protoplanetary disk. For example, the material that collects to form the Earth has significant contributions from regions interior to Mercury and exterior to Mars [6]. In this sense, the provenance of the Earth and Venus is the entirety of the inner solar system. Because of the stochastic nature of this last stage and the small number of participating embryos, there may have been significant fluctuations around the mean composition – for any given giant impact – for the accumulating planets.

Thus, the Earth and Moon are not similar because they both record the '1 AU' oxygen isotope signature. The Earth is a mixture of inner solar system material, whereas the runaway embryos from which it formed were unmixed local samples of the heterogeneous protoplanetary disk. The present composition of the Earth only reveals the average composition of the contributing impactors, whereas key to our story is the scatter between the embryos. The question we now address is: what if the moon-forming impactor had been not only Mars-sized, but Mars itself. In this case, could resulting post-impact processes homogenize the oxygen isotope composition to that of the present Earth-Moon system?

A Proposed Solution: Immediately after the giant impact, the Earth-Moon system is largely molten and partially vaporized [7]. The proto-lunar material forms a circumterrestrial magma disk, and an extended silicate vapor atmosphere surrounds both the disk and the planet (figure 2).

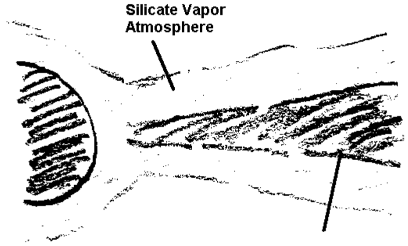

Figure 2. Schematic of Earth and proto-lunar disk.

The atmosphere is initially extremely hot, reaching temperatures of several thousand degrees. Both the Earth and the magma disk are vigorously convective, as is the silicate vapor atmosphere surrounding them. The extended disk atmosphere, with about 10% the mass of the magma disk, is contiguous with the silicate vapor atmosphere of Earth and can therefore act as an exchange medium communicating isotopic signals between the two liquid reservoirs with which it is in contact. Evaporative exchange between the liquid and the vapor atmosphere is quite fast. The timescale to exchange the mass of the disk atmosphere is given by:

$$T \sim \sigma V_t / P \alpha_c \qquad (1)$$

where σ is the surface mass density of the atmosphere, V_t is the molecular thermal speed, P is the vapor pressure, and α_c is the condensation coefficient, which represents the fraction of downward moving gas molecules which enter the liquid phase. For forsterite, its numerical value is ~0.1 [8]. This gives an exchange timescale of the order of a week. Since the proto-lunar magma disk is only ~10x more massive than the disk atmosphere, it can exchange its mass with the vapor atmosphere on a timescale only an order of magnitude longer. In reality, the timescale is even shorter because the exchange is occurring in a two-phase medium (vapor with liquid droplets) that enhances the surface area for evaporative exchange compared to a smooth liquid/vapor interface [9].

To estimate the efficiency of mixing between the Earth and the proto-lunar disk, we parameterize the diffusivity of the atmosphere as $D = \alpha H C_s$ where H is the scale height of the disk and Cs is the sound speed. α is a measure of the efficiency of turbulent mixing. Scaling suggests that the timescale for diffusion across the system is:

$$T \sim L^2 / (\alpha H C_s) \qquad (2)$$

where L is a typical length scale. For radial diffusion across the extent of the disk (several earth radii), with $\alpha \sim 10^{-2}$, the timescale is on the order of a year. The diffusivity, calculated as the product of the length scale and convective velocity yields a similar timescale. Since the silicate vapor disk may persist for a period of hundreds of years [9], the system may undergo significant mixing. We will present calculations of the extent of diffusive transport between the proto-Earth and the disk, and discuss implications for oxygen isotope compositions.

Because of several uncertainties, the extent of the mixing is uncertain. For example, since the Moon forms from the outermost disk material, it may not fully participate in the diffusion occurring between the inner regions and the Earth. The outermost regions of the disk cool faster, perhaps freezing and cutting off a fraction of the proto-lunar material from isotopic exchange. Despite these uncertainties, it is likely that the moon will form with a significantly more Earth-like oxygen isotope signature than the impactor which triggered its formation.

Conclusions: The contrasting accretion styles of the Earth and the moon-forming impactor suggest that they did not have identical source regions, and hence oxygen isotope compositions. Our model suggests that in the aftermath of the giant impact, the proto-Earth and the proto-lunar magma disk may have approached diffusive equilibrium with respect to oxygen isotopes. Since this process would have occurred at high temperatures, this also predicts that the delta-values of the bulk silicate Earth and bulk silicate Moon will be the same. Resolving the oxygen isotope story in the inner solar system, for example, by sampling Venus and Mercury, may help to resolve the long-standing problem of the provenance of the terrestrial planets.

References: [1] Wiechert U. et al. (2001) *Science*, 294, 345-348. [2] Canup R. M. et al. (2001) *Nature*, 412, 708-712. [3] Cameron, A. G. W. (1997) *Icarus*, 126, 126-137. [4] Clayton, R. N. (1993) *Ann. Rev. Earth Planet. Sci.* 21, 115. [5] Chambers J. E. (2004) *Earth and Planet. Sci. Letters*, 223, 241-252. [6] Chambers, J. E. (2001) *Icarus* 152, 205-224. [7] Stevenson, D. J. (1987) *Ann. Rev. Earth Planet. Sci.* 15, 271-315. [8] Inaba, H. et al. (2001) *LPSCXXXII* 1837 [9] Thompson, C. and Stevenson, D. (1988) *Ap.J.* 333, 452-481.