ISOTOPIC EQUILIBRATION OF EARTH'S MANTLE AND THE MOON SUBSEQUENT TO THE GIANT IMPACT? A. Zindler and S. B. Jacobsen, Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA 02138 (zindler@eps.harvard.edu).

Introduction: Striking, mass-independent oxygen [1], chromium [2], and tungsten [3] isotopic similarities between the Earth's mantle and the Moon, which are readily distinguished from most other Solar System materials, provide a critical but troublesome test for models of lunar formation. In the context of the giant impact theory, the leading hypothesis for the origin of the Moon [e.g., 4, 5], these isotopic similarities were once thought to document formation of both the Earth and the impactor at similar heliocentric distances in an isotopically zoned solar nebula. However, current models suggest that terrestrial planet formation culminates with a period of major impacts between growing planets and planetary embryos, thought to sample a large radial zone of the nebula extending to beyond the radius of Mars [6, 7]. The giant impactor that formed the Moon, therefore, is unlikely to have originated at one AU, or to have had isotopic characteristics indistinguishable from the proto-Earth. Suggestions that the Moon formed from material ejected from the Earth's mantle by the impactor [11], or from mass-relative proportions of Earth and impactor, are incompatible with SPH models which overwhelmingly predict that 80% or more of the protolunar material originates from the impactor [see 5 and references therein]. In view of these considerations, one must conclude either that significant aspects of current models are in need of revision, or attribute important aspects of the Earth-Moon system to a rather large coincidence.

A Novel Approach: Pahlevan and Stevenson [8] explored a very different potential solution to this problem: that the Earth and protolunar disk, largely molten but isotopically dissimilar in the immediate aftermath of the giant impact, were able to achieve oxygen isotopic equilibrium via exchange of oxygen through the shared, hot, dense, silicate vapor atmosphere that prevailed for a short time between the impact and lunar accretion [5]. Subject to radiative cooling with an effective photospheric temperature of 2000°K [9], Pahlevan and Stevenson [8] argue that the cooling timescale for the disk material, which essentially defines the time available for equilibration, can be as long as 10^2 to 10^3 y (as compared to 3×10^3 y for the Earth). In this context, they construct semiquantitative but compelling arguments that convection within the Earth, disk and atmosphere, as well as the liquid-vapor exchange process, proceed at rates which are sufficient to permit the equilibration to occur. They conclude by noting that the limiting step is likely radial mixing through the atmosphere of the disk, but that this, too, is sufficiently rapid to allow the Earth-disk isotopic equilibration to take place.

Oxygen Isotope Mixing: As Pahlevan and Stevenson [8] did not quantitatively explore the timescale for oxygen isotope mixing in the context of their model, we decided to do this in an effort to further evaluate the viability of the process. Using the boundary conditions of Pahlevan and Stevenson [8], we explored the oxygen isotope evolution of the system as a three-reservoir mixing problem. We assumed that each of the reservoirs, Earth, disk and vapor atmosphere, remained homogeneous due to vigorous internal convection. The disk comprises approximately 80% melt and 20% silicate vapor. Earth-vapor and disk-vapor fluxes were scaled to one another according to the ratio of the surface area of the Earth to that of a 2-lunar-mass disk centered on the Roche limit of the Earth-Moon system (~1:11). For this case, the magnitude of the melt-vapor fluxes per unit area are the same for the disk and the Earth. The initial Earth-disk discrepancy in $\Delta^{17}O$ is taken as ~0.307‰, the approximate magnitude of the mean difference between Earth and Mars, and the target value for equilibration is taken as 0.005‰ (the level at which analytical differentiation becomes difficult).

With the ratio of the two fluxes fixed, the critical parameter becomes the total amount of material exchanged between the Earth and the vapor or the disk and the vapor over the course of the equilibration time period. For the chosen parameters, the target result is obtained when the total disk-vapor exchange is about 1.4 Earth masses (see Fig. 2).

Discussion: Pahlevan and Stevenson [8] argue that the melt-vapor exchange can be modeled as a continual rainout of vapor condensate that forms in response to radiative cooling at the top of the atmosphere. The timescale to condense the mass of the vapor and advect its composition to the molten disk is about 2 y for the present set of model parameters [8]. This is equivalent to a melt-vapor flux of ~0.1 $kg\ m^{-2}\ s^{-1}$. At this rate, ~500 y is required to attain oxygen isotope equilibrium between the disk and the Earth (Fig. 1). As the cooling timescale of the disk was estimated to be 10^2 to 10^3 y [8], it becomes clear that this timescale is indeed very important in assessing the viability of the model.

Cooling of the model disk would occur on a timescale of only a few years were it not for the liberation of thermal energy due to viscous dissipation during spreading [9]. In fact, the energy released per unit mass substantially exceeds the latent heat of vaporization for silicates [5]. Thompson and Stevenson [9] show that a balance between viscous heating and radiative cooling permit the disk to remain in a "marginally unstable" state, substantially lengthening timescales for both cooling and spreading. For our purposes, we need to know whether this can sustain a molten disk long enough to permit isotopic equilibration.

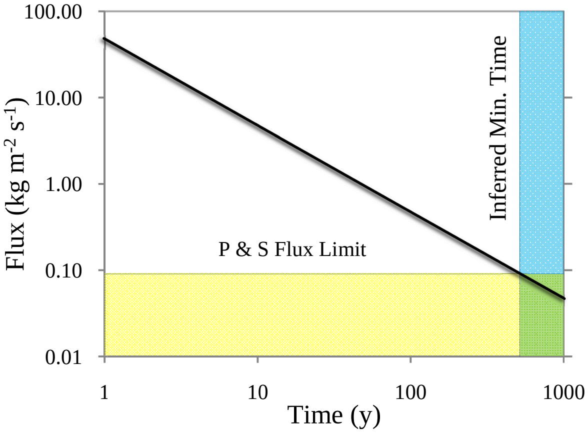

Fig. 1: Flux (kg m^{-2} s^{-1}) vs. equilibration time. The maximum flux between the molten disk and vapor given by Pahlevan and Stevenson [8] is shown, as is the minimum equilibration time inferred from that flux.

Thompson and Stevenson [9] derive an expression for the spreading time of a viscous disk (eqn. 46) that yields a time of about 20 y for the current set of parameters. Though short, this value is about 40 times slower than the spreading time given by eqn. 5 of Ward and Cameron [10], which ignores the disk's thermal budget [5]. The 20 y spreading time is in agreement with the 10 to 100 y range given by Thompson and Stevenson [9] in their conclusions. The 100 y end of their range seems to require that the entire disk be restricted to the region interior to the Roche limit of the Earth-Moon system, and so minimize its surface area and radiative cooling rate. The 20 y timescale is also consistent with a comparison of the total heating due to viscous dissipation [5], and the radiative cooling rate for a disk centered on the Roche limit.

It seems likely to us, therefore, that the time available for isotopic equilibration between the Earth and protolunar disk via vapor-liquid exchange is substantially less than 100 y, although the time required to eradicate an Earth-Mars sized Δ^{17}O difference is ~500 y, in the context of the three-box exchange model described here (see Fig. 2). Were the Δ^{17}O difference only 0.031‰, a tenth of the Earth-Mars difference, the required time would still be more than 200 y. Pahlevan and Stevenson [8] identified radial mixing within the vapor portion of the disk as the rate-limiting step for the equilibration process. Though we have not yet attempted to quantify this effect, it will *increase* the calculated equilibration times due to the introduction of a time constant for the radial homogenization of the vapor [see Fig. 4 of ref. 8], an aspect of the process we have assumed to be instantaneous.

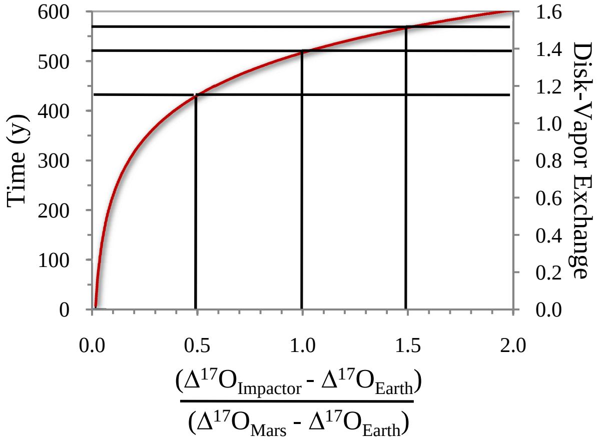

Fig. 2. The relative Δ^{17}O difference between Earth and the impactor vs. time in years (left-hand axis), and the total disk-vapor flux, measured in Earth masses (right-hand axis).

We conclude, therefore, that liquid-vapor exchange subsequent to the giant impact does not represent a compelling explanation for the isotopic similarities of the Earth and Moon in the context of current lunar formation theories. While there may be no obvious reason to suppose that SPH simulations are inaccurate in their predictions that the Moon be predominantly formed from impactor material [8], future studies should pay particular attention to testing the robustness of this requirement. The alternatives, unfortunately, are similarly at odds with current models of lunar and planetary formation. Ringwood's [11] assertion that the Moon formed from the Earth's mantle, remains a difficult hypothesis to reject out of hand.

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