RETHINKING LUNAR FORMATION: BACK TO THE FUTURE? A. Zindler and S. B. Jacobsen, Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA 02138 (zindler@eps.harvard.edu).

Introduction: The giant impact hypothesis stands alone as the most widely accepted, carefully and thoroughly researched model for the formation of the Moon [e.g. 1, 2-5]. It enjoys widespread support within the scientific community as well as an impressive level of public recognition. The lack of contention that attends the model, the sense of a difficult problem well solved, should perhaps cause us to remember Ted Ringwood, that great contender. He led the scientific investigation of the Earth-Moon system with remarkable acumen for many years, and devoted a sizeable fraction of the final chapter of his illustrious career to questioning and challenging the nascent giant impact hypothesis [6-10]. His principal objections were based on his assessment that similarities between the abundance patterns of moderately siderophile elements in the Earth's mantle and the moon could not have been produced by the vagaries of complex core formation processes acting independently in two separate bodies of very different size, with vastly different pressure-temperature regimes and accretion histories. Ringwood was, therefore, adamant in his conviction that the moon had to have been predominantly derived from the Earth's mantle. This was not exactly an all-out rejection of the giant impact hypothesis, as Ringwood was always willing to have the proto-lunar material ejected from the Earth by an impacting planetesimal, though perhaps not a giant one, during the latter stages of accretion.

Ringwood's principal objection challenged the single most robust and reproducible result to have emerged from 24 years of Smoothed Particle Hydrodynamic (SPH) investigations of the giant impact hypothesis – that the proto-lunar disk is predominantly comprised of material ejected from the mantle of the *impactor*, not the Earth [1-4, 11-13]. Canup [5] bemoans this result and, for the first time, investigates the effects of pre-impact rotation on impact outcomes. New, potentially feasible lunar impact scenarios were discovered, but, in all cases, the disk still forms from the impactor. Another issue that Ringwood took exception with was the assumption or requirement that the anomalous angular momentum of the Earth-Moon system be supplied by a single collision event which must also form the moon. This constraint has been used both for experimental design and in the selection of "successful" experiments. Ringwood felt that this was unnecessarily restrictive and impractical. He thought that a very large impact at the very end of accretion would melt the Earth's mantle, and, in the absence of further accretional growth to facilitate mixing, the mantle would become semi-permanently gravitationally stratified, a condition not observed today. Ringwood, therefore, favored a model involving one or more small, cold, even icy, high-velocity planetesimals from the outer solar system that impact a hot or partially molten, not-quite-fully-grown Earth at a relatively high angle, ejecting material from, predominantly, the Earth's mantle into a proto-lunar disk.

Ringwood's observations were, in fact, unavoidably model dependent, framed by marked uncertainty in lunar composition, and his model scenarios were more intuitive than quantitative. On the other hand, the SPH models are, indeed, a bit coarse. The state and position of the materials are tracked very accurately, but the particles are very large, typically ≥ 250 km in diameter, and chemical interactions are not possible [5].

The Isotopic Evidence: One can only imagine what Ringwood would say today if he were presented with the striking, mass-independent and largely model-independent oxygen [14], tungsten [15], and chromium [16] isotopic similarities between the Earth's mantle and the Moon – identical to one another, and distinct from most other Solar System materials. He would certainly experience the sweet thrill of long-awaited vindication. Until, that is, he learned that the giant impact model, despite its impressive array of adjustable parameters, continues to amass evidence that the Moon *must* derive from the impactor – that so many of his arguments and ideas passed quietly from view not long after his voice was stilled. In all seriousness, the current situation has evolved into a first-rate conundrum. The not-very-attractive options include: 1) find a different but complementary technique that can be used to independently test and evaluate the SPH simulation outcomes; 2) reject the context provided by rapidly evolving dynamical models for planetary formation; 3) conclude that the genetic relationship between the only two planets we humans have actually walked on is nothing more than a highly improbable coincidence; or, 4) accept the vapor equilibration model of Pahlevan and Stevenson [17].

Vapor Mediated Equilibration: Though seemingly improbable at first glance, Pahlevan and Stevenson's very original model is, in a way, the most palatable of the available options. And it represents a distinctly clever approach to an increasingly perplexing problem. In short, Pahlevan and Stevenson [17] contend 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 [3]. We previously [18] evaluated the potential for vapor-mediated Earth-disk oxygen isotopic equilibration using a simple 3-box model, along with Pahlevan and Stevenson's liquid-vapor exchange rates, and disk parameters. An Earth-disk difference in ΔO^{17} of ~0.307‰, the approximate difference between Earth and Mars, is effectively erased in about 500 y. If the initial ΔO^{17} discrepancy is reduced by a factor of 10, more than 200 y is still required for a close approach to equilibrium. Thus, the longevity of the liquid-vapor disk is a critical parameter for evaluating model feasibility. Subsequent to the impact, the disk is a very hot, vapor-melt mixture, but due to its small mass and large surface area, its radiative cooling time is < 5 y. However, the energy released per unit mass as the disk viscously spreads exceeds the latent heat of vaporization for silicate by a factor of about 3. A negative feedback between the viscous dissipation and vaporization serves to modulate the spreading rate and substantially lengthen the total cooling time for the disk. Even so, maintaining the disk in a liquid state for more than 25 – 50 y is only possible for a compact disk with a small surface area to volume ratio, if the entire disk remains within the Roche limit, where tidal forces prevent lunar accretion.

Pahlevan and Stevenson [17] discuss two additional pitfalls for the model. First, gas density at the dynamical interface between the disk and Earth may be insufficient to facilitate effective exchange across the interface. Second, radial transport within the disk, essential for conveyance of the local isotope signal to distal regions of the disk from which material the moon will eventually form. Radial transport is modeled as an eddy diffusivity, where efficiency is related to the size of the largest convective eddies. Effective radial transport within the disk apparently requires an unrealistically optimistic estimate for eddy size.

Hydrostatic Equilibrium: Finally, we briefly consider the most basic requirement of the equilibration model – that the disk achieve and maintain a state of hydrostatic equilibrium [19, 20]. Absent this, the vapor will continually undergo adiabatic expansion toward ∞. Ongoing hydrodynamic escape limits the time available for diffusive exchange between gas and the disk. The resulting mass outflow contributes to cooling and shortens the life of the disk. Large-scale hydrodynamic instability may develop in the aftermath of a large impact, or with the rapid development of instabilities induced by material irregularities in a spreading disk

Discussion: Efficient and prolonged exchange of material between the Earth and Moon through a shared silicate vapor atmosphere is unlikely to occur or account for recognized isotopic similarities between the Earth and Moon [17, 18, 20]. While the ultimate state of isotopic equilibrium is easy to predict and recognize, the range of chemical fractionations that may occur at the very high temperatures and low pressures that prevail in a post-impact Earth-Moon system will almost certainly lead to very unusual and distinctive elemental fractionations and associations governed by differential volatility. Failure to recognize such effects in lunar or terrestrial samples argues against a pivotal role for vapor transfer in establishing chemical relationships between the Earth and Moon.

In conclusion: Creative and compelling solutions for the lunar- formation conundrum are in short supply. Moving forward may require that we make a concerted effort to *explain* the oxygen and tungsten isotopic similarities between the Earth and Moon, not just *explain them away*. It might also be a good idea to haul out some of Ringwood's old models and arguments, dust them off, bring them up to date, and carefully consider any that appear to be standing the test of time.

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