WAS THE ATMOSPHERE LOST DURING THE MOON-FORMING GIANT IMPACT? S. J. Lock, S. T. Stewart and S. Mukhopadhyay, Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA 02138 (slock@fas.harvard.edu)

Introduction: The relative abundances of volatiles in the Earth is significantly different than in chondrites [1]. In particular, the nitrogen and carbon budgets are depleted relative to hydrogen by different amounts. Therefore, in order to generate the present-day volatile budget of the Earth from currently observed source materials, a mechanism that preferentially removed N and C while retaining H must have acted during planet formation [1].

It has been suggested that the deficiency of N [1] and C [2] relative to H could be explained by sequestration of these elements in iron during core formation. However, Tucker & Mukhopadhyay [3] point out that C is more siderophile than N; if these elements were partitioned into the core, one would expect a lower C/N ratio in the bulk silicate Earth than in chondrites. The observed C/N is actually higher [1], contradicting the core sequestration hypothesis.

An alternative solution, proposed by [3], is that the depletion in N and C relative to H can be explained by atmospheric loss during a giant impact. If the proto-Earth had a condensed ocean prior to the impact, then N and C would be lost in the form of the atmophile species N_2 and CO_2, while H would be preferentially retained as water in the ocean. Here we consider the potential for this elemental fractionation to occur as a result of the Moon-forming impact (MFI). We present calculations for the magnitude of atmospheric and oceanic loss during different Moon formation models and discuss the implications for interpreting Earth's volatile inventory.

Comparison of Moon Formation Models: The canonical Moon-forming impact scenario is a Mars-mass impactor striking the proto-Earth at the escape velocity [4]. Recently, however, in an attempt to explain the isotopic similarity between the Earth and Moon, two new models have been developed that rely on the breaking of the angular momentum constraint on the impact event and a subsequent dynamical resonance to transfer angular momentum away from the Earth-Moon system [5]. The first of these involves a more head-on impact onto a fast-spinning Earth [5] and the second is a collision between two ~half Earth-mass bodies [6]. Compared to the canonical impact, both new impact models have larger specific impact energies [7].

Giant impacts blow off the far field atmosphere via the kick provided to the bottom of an atmospheric column by the impact shock breaking out at the surface. The magnitude of loss is controlled by the ratio of the particle velocity at the surface of the planet to the escape velocity; the presence of an ocean enhances the amount of atmosphere lost [8]. The surface particle velocities reflect the spatial distribution of shock pressures within the target, which is sensitive to the impact geometry. In order to calculate atmospheric loss from a particular impact scenario, we combine the radial surface velocity field from 3D impact simulations and the results from 1D calculations of the shock driven loss in a column of atmosphere [8, 9]. In addition, we have extended the 1D models to consider loss from planets with pre-impact rotation. Generally, substantial atmospheric loss occurs for specific impact energies $Q_S > 10^6$ J/kg in the presence of an ocean and $>10^7$ J/kg without an ocean [7].

The canonical Moon-forming impact [4] results in very little atmospheric loss (Q_S~0.5-1.7×10^6 J/kg). Even with a large ocean to atmospheric mass ratio, the loss in such an impact is <~30% and dominated by the contact area between the two bodies. Genda & Abe [8] found substantial atmospheric loss with an ocean; however, they considered a single mean value for the surface particle velocity which was larger than the mean value determined from our 3D simulations. We find that the distribution of surface velocities is strongly skewed to the low end.

For Moon-forming impacts between bodies of similar mass [6], the range of outcomes is more varied (Q_S~2-30×10^6 J/kg). For impacts close to the escape velocity (V_{esc}), atmospheric loss is restricted to the impacted hemisphere of the two bodies; hence, loss is generally <~50%, irrespective of the presence of an ocean. However, for the higher energy cases (~10^7 J/kg), more substantial atmospheric loss is possible if there was a pre-impact ocean.

Models with a pre-impact fast-spinning Earth [5] involve more head-on impacts with high impact velocities (~1.5-3 V_{esc}). Because the impactors are small, the total specific energy of the event overlaps with the two half-Earths scenario (Q_S~3.5-14×10^6 J/kg). Because impact energy is well coupled to the shock wave in the target by nongrazing impacts, a substantial fraction (>~50%) of the atmosphere is lost in all cases in the presence of an ocean.

For most MFI scenarios, most of the pre-impact ocean is retained. However, it is possible to lose a substantial fraction of the ocean in addition to the atmosphere for the most energetic cases [7]. These cases could remove a high fraction of the atmosphere even without a pre-impact ocean. Note that the highest energy range for the high angular momentum MFI scenarios (>10^7 J/kg) are also likely to lead to wide-spread shock-induced melting of the Earth [7]. Whether or not the lower energy scenarios fully melt the Earth depends on the details of the heterogeneous deposition of impact energy.

Implications for Earth's Volatile Fractionation: Based on the different volatile abundance ratios in the Earth and chondrites [1] and the similar D/H ratios of the Earth and Moon [10], the majority (>~70%) of Earth's water accreted prior to the Moon-forming giant impact. Thus, Earth likely had an ocean at the time of the MFI.

The canonical Moon formation scenario, and other giant impacts of similar specific energy, do not substantially remove the Earth's pre-impact atmosphere. Therefore, such giant impact events cannot produce the observed depletion in N and C in the bulk silicate Earth relative to chondrites.

The high angular momentum Moon formation scenarios may contribute to Earth's volatile fractionation by bulk ejection of N_2 and CO_2 and retention of H_2O. Compared to different classes of chondrites, Earth's H/N ratio is enhanced by factors of a few to more than an order of magnitude. At the highest impact energies (>~10^7 J/kg), the ratio of ocean fraction retained to atmospheric fraction retained after a giant impact can be more than a factor of 10, but factors of few are more likely for the proposed range of MFI events [7].

Tucker and Mukhopadhyay [3] argue for multiple partial mantle magma oceans and atmospheric loss events during Earth's accretion. Our estimate of bulk fractionation of surface volatile reservoirs by giant impacts appears to be able to achieve the magnitude necessary for the observations. Note that there is a range of specific impact energies, $10^6<Q_S<10^7$ J/kg, that lead to substantial atmospheric loss and retention of an ocean without necessarily melting of the whole mantle [7]. Whether or not full mantle melting is achieved at a later time during the impact event depends on the details of the impact geometry and presently unresolved mixing processes. Quantitatively evaluating the possible magnitude of C/H and N/H fractionation generated by different MFI scenarios will also require consideration of outgassing and re-equilibration with the magma ocean during possible sequences of giant impacts during Earth's accretion.

Conclusions: Earth's volatile inventory, which is fractionated compared to chondrites, provides an additional constraint on Earth's accretion history. We suggest that giant impacts contributed significantly to the observed volatile fractionation pattern. A high angular momentum Moon-forming giant impact would have contributed to Earth's overall depletion of N and C relative to H without isotopic fractionation by bulk ejection of the atmosphere and retention of the ocean. The canonical Moon formation scenario, and giant impacts with similar specific energy, would not eject a substantial fraction of the pre-impact atmosphere and lead to negligible fractionation between the atmosphere and ocean volatile reservoirs.

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