ATMOSPHERIC LOSS DURING HIGH ANGULAR MOMENTUM GIANT IMPACTS.

Simon J. Lock and Sarah T. Stewart. Department of Earth and Planetary Sciences, Harvard University, 20 Oxford Street, Cambridge, MA 02138 (slock@fas.harvard.edu, sstewart@eps.harvard.edu)

Introduction. During the end stage of planet formation, terrestrial planets are expected to experience a number of giant impacts. Understanding how much of the planet's atmosphere is lost to space during such collisions is vital to be able to determine the origin and evolution of planetary atmospheres. Recently, geochemical observations [1, 2] and high angular momentum models for the Moon-forming impact [3, 4] have renewed interest in the topic of atmospheric loss during giant impacts. Impact-driven loss is proposed to be an important process in explaining the origin of the Earth's atmosphere and the variability of terrestrial planet atmospheres [1, 2, 5].

In the canonical models of the Moon-forming impact, a Mars-sized impactor obliquely hit the proto-Earth near the escape velocity [e.g. 6]. In such collisions, atmospheric loss can occur either from direct ejection near the impact site or due to the ground 'kick' provided by the impact shock wave. Genda and Abe [7] showed that the shock wave would not cause a significant loss of atmosphere during the canonical Moon-forming impact. They later demonstrated [8] that the presence of an ocean could enhance the loss of the atmosphere, particularly on the smaller body in the collision or over multiple impact events. However, at present it is widely believed that the Moon-forming giant impact event did not lead to significant atmospheric loss from the proto-Earth.

The canonical Moon-formation scenario [e.g. 6] was constrained by the angular momentum of the present Earth-Moon system, in which the Earth had a ~5 hour spin period just after Moon formation. However, with this constraint, it is not possible to form a lunar disk with enough proto-Earth material in order to explain the identical isotopic composition of the Earth and Moon. Recently, however, Ćuk and Stewart [3] offered a solution to this problem by showing that the Earth-Moon system could have lost angular momentum in an orbital resonance after the impact. They then showed that it was possible that a smaller, high velocity impactor incident on a fast-rotating Earth (2 to 3 hr spin period) could generate the observed isotopic similarity. An isotopically similar disk could also be formed by a graze-and-merge impact between two approximately equal-sized bodies [4]. In these new models, it is likely that more of the atmosphere could be lost, compared to the canonical giant impact scenario, because the Earth would be near or exceeding its spin stability limit during the impact event.

A larger atmospheric loss fraction during Moon formation would be consistent with the noble gas isotopic data. Mukhopadhyay et al. [1], building on previous work, have shown that any pre-existing atmosphere derived from mantle outgassing or the solar nebula that existed on the Earth before the Moon-forming impact has been mostly lost (>~70% lost with larger loss fractions favored). In addition, Tucker and Mukhopadhyay [2] have used the ^{3}He/^{22}Ne ratio of the mantle to argue that the Earth must have experienced multiple episodes of magma ocean degassing followed by atmospheric loss. The most obvious explanation for such occurrences is a series of giant impacts expelling the atmosphere and melting the upper layers of the Earth [2]. Together this evidence suggests strongly that significant atmospheric loss must occur during at least some giant impacts.

It has also been suggested [5] that a greater loss fraction in high angular momentum impacts compared to low angular momentum cases could explain the differences between the atmospheres of the terrestrial planets. The difference in noble gases between the atmospheres of Earth and Venus could be simply explained by the former losing its nebular-derived atmosphere in a high angular momentum impact and the latter not.

It is therefore imperative to quantify the atmospheric loss experienced in high angular momentum giant impacts to understand whether such collisions could provide the desired mechanism for greater atmospheric loss. The results of our preliminary calculations, reported below, suggest that this is indeed the case but more rigorous work is required. We will present the results from more detailed calculations as described below.

Preliminary Results - A Proof of Concept. To illustrate the potential for higher atmospheric loss fractions in high-spin impact models [3], we have performed some preliminary calculations based on smoothed particle hydrodynamics (SPH) simulations and the 1-dimensional (1D) atmospheric loss calculations of Genda and Abe [7, 8] for the non-spinning case. We have used the SPH simulations, of both the canonical Moon-forming models and high angular momentum impacts, to estimate the maximum surface velocity at each point on the target body. To do this we have taken the maximum velocity of each of the SPH particles initially on the surface of the target body as the maximum ground velocity. We have then used the scaling relations between ground velocity and atmospheric loss [7, 8] to approximate the global atmospheric loss from these velocities.

For the classical angular momentum constrained Moon-forming impact [e.g. 6], we estimated that only a few 10's % of the atmosphere would be lost depending on the mass of the oceans on the proto-Earth. These are similar to the results of Genda and Abe [7, 8].

In the case of Ćuk and Stewart's fast-spinning Earth impact (using the example in Fig. 1 of [3]), we found that 60–100% of the atmosphere would be lost, again depending on the mass of the Earth's oceans. This simple calculation demonstrates that significantly higher atmospheric loss fractions can be achieved in high angular momentum impacts.

There are, however, several limitations of this approach. Firstly, the scaling relations calculated by Genda and Abe [7, 8] are for a single shock propagating radially outwards into a stationary atmosphere in a non-rotating frame. Our simple estimate does not make any corrections due to changes in geometry, gradual accelerations rather than rapid rise time shocks, or the effects of rotation. Furthermore, the SPH simulations do not include the crust or an ocean and have a low resolution of the shock wave interaction with the surface. Therefore, the surface velocities need to be reassessed with high-resolution simulations. In addition, the exact collisional parameters for the Moon formation event are not well constrained and two very different categories of giant impact scenarios have been proposed [3, 4]. These concerns therefore warrant a more rigorous examination of the atmospheric loss from high angular momentum collisions.

Approach for Detailed Modeling. SPH simulations of the high angular momentum impacts [3, 4] show a number of potential mechanisms for atmospheric loss. These include direct ejection from the impact site, the ground acceleration due to the initial impact shock wave, and possible acceleration of atmospheric gases by spiral arms of material. Therefore, in order to tackle the problem of atmospheric loss it is necessary to break it down and address each mechanism separately.

We will calculate the effect of the shock wave breaking out of the surface of a rotating planet. In order to examine the region of the atmosphere most affected by rotation, we will model the atmospheric loss at the equator due to a 'kick' at the surface. This will be done using a 1D Lagrangian fluid dynamics code in cylindrical coordinates but in addition taking into account the azimuthal velocities of the air parcels. The equatorial rotating planet calculation will complement the work done on non-rotating bodies [7, 8], and these two regimes will bound the atmospheric loss from each point on the surface. Genda and Abe [7, 8] found that the initial state of the atmosphere had little impact on their results; however, we will examine how a varied atmospheric structure will affect our results. We will also consider the effect of a surface ocean on the loss fraction.

These calculations will quantify atmospheric loss with respect to the initial ground motion. The surface velocity field for the impacts will be refined by conducting high-resolution calculations using the adaptive mesh capabilities of the Eulerian CTH shock physics code. We will then be able to make an estimate of the loss fraction due to this mechanism.

In addition, we will attempt to understand the potential for atmospheric loss caused by the slow acceleration of the atmosphere by the spiral arms formed later in the collision process. The structure and motion of the spiral arms are complex but we will take a simple approach by modeling a solid driver accelerating the atmosphere. The state of the atmosphere will be more complicated than for the initial shock and could consist of a large fraction of vaporized rock from the impact. Due to its complex and variable nature, the atmospheric loss due to this mechanism may prove difficult to reliably quantify.

Summary. There is geochemical evidence that the Earth lost its atmosphere multiple times during its formation including during the final, Moon-forming giant impact. Although previous calculations have shown significant atmospheric loss to be unlikely in the canonical Moon formation scenario, recent work has suggested a high angular momentum impact origin for the Moon [3, 4]. In these new models, it may be possible to achieve a large fraction of atmospheric loss that would explain the geochemical data. We intend to produce models to quantify the atmospheric loss in these high angular momentum impact events.

A potential application of such calculations would be to constrain the rotation rate of the proto-Earth in high-spin impact models using the bounds on the loss fraction provided by the noble gas isotope data. This would provide a vital constraint on dynamical models of the formation of the Earth-Moon system.

Acknowledgements. This work was supported by NASA Origins #NNX11AK93G.

References: [1] Mukhopadhyay, S., et al. (in review) *Nature*. [2] Tucker, J.M. and S. Mukhopadhyay LPSC 44 (and in review in *EPSL)*. [3] Ćuk, M. and S.T. Stewart (2012) *Science* **338**, 1047. [4] Canup, R.M. (2012) *Science* **338**, 1052. [5] Stewart, S.T. and S. Mukhopadhyay (2013) *LPSC* **44**. [6] Canup, R.M. and E. Asphaug (2001) *Nature* **412**, 708. [7] Genda, H. and Y. Abe (2003) *Icarus* **164**, 149. [8] Genda, H. and Y. Abe (2005) *Nature* **433**, 842.