IMPACT TRIGGERED ATMOSPHERIC LOSS AND OUTGASSING DURING EARTH'S LATE ACCRETION. H. E. Schlichting[1,2], L. T. Elkins-Tanton[3], B. Black[4] and S. Marchi[5], [1]Department of Earth, Planetary and Space Sciences, University of California Los Angeles, Los Angeles, CA 90095, hilke@ucla.edu. [2] Department of Earth, Atmospheric and Planetary Sciences, MIT, Cambridge, MA 02139. [3]School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287, [4]Department of Earth and Atmospheric Sciences, City University of New York, New York City, NY 10017. [5]Southwest Research Institute, Boulder, CO 80302

Introduction: Determining the origin of Earth's volatiles and quantifying atmospheric loss during planet formation is crucial for understanding the conditions prevailing on the early Earth. Atmospheric loss caused by small planetesimal/asteroid impacts is many orders of magnitude more efficient per unit impactor mass for terrestrial planets than giant impacts [1]. The higher atmospheric mass-loss-efficiency of small impactors is due to the fact that most of their impact energy and momentum is directly available for local atmospheric mass loss, whereas in the giant impact regime a lot of energy and momentum is 'wasted' by having to create a strong shock that can transverse the entirety of the planet such that global atmospheric loss can be achieved. For the current atmospheric mass of the Earth, small impactors are about five orders of magnitude more efficient (per unit impactor mass) than giant impacts, implying that atmospheric mass loss must have been common throughout planet formation [1]. Here we investigate the atmospheric evolution of the Earth after the end of the giant impact phase during Earth's late accretion by calculating both the atmospheric erosion due to impacts and the associated outgassing.

Results: The atmosphere of the early Earth is set by the interplay of three main processes: Atmospheric erosion by impacts, outgassing and volatile delivery by impactors. We investigate the relative importance of all three processes by calculating the atmospheric erosion due to an impactor population inferred from the lunar cratering record and scaled to the Earth [2] and by determining the melt-volume [2] and likely associated outgassing from the magma 'ponds' created by the impactors [3].

Atmospheric erosion by impacts: We find in the absence of any volatile delivery and outgassing, that the population of late impactors inferred from the lunar cratering record containing less than 0.5% of the mass of the Earth is able to erode the entire current Earth's atmosphere (see Figure 1). This implies that an interplay of erosion, outgassing and volatile delivery is likely responsible for determining the atmospheric mass and composition of the early Earth.

Impact triggered outgassing: Whether or not impacts lead to net atmospheric loss or gain depends

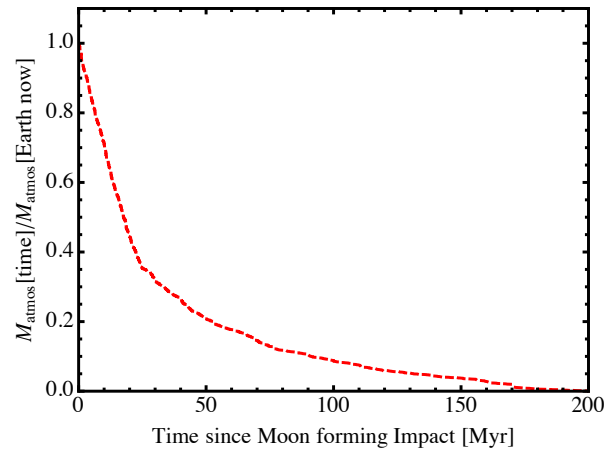

Figure 1: Atmospheric erosion during Earth's late accretion phase. In the absence of any volatile delivery and outgassing, the population of late impactors inferred from the lunar cratering record containing less than 0.5% of the mass of the Earth [2, 4] is able to erode the entire current Earth's atmosphere [1].

on the amount of volatiles that they deliver and the amount of outgassing they cause compared to the atmospheric loss they trigger. Figure 2 gives a comparison of these three processes as a function of impactor size for water and CO_2. The atmospheric loss is calculated for velocities and impactor properties relevant for the late accretion phase [1, 2, 4, 5]. For each impactor the melt production is determined [3] and the associated outgassing is calculated for both CO_2 and H_2O. As initial condition we use the final state of magna ocean models for a high, medium and low volatile content of the mantle [6]. The high case assumed 1wt% and 0.5 wt% initial H_2O and CO_2, respectively with 2% interstitial liquid. The medium case assumed 0.1wt% and 0.05 wt% initial H_2O and CO_2, respectively with 2% interstitial liquid. The low case assumed 0.02 wt% and 0.01 wt% initial H_2O and CO_2, respectively with no interstitial liquid. Only the high and medium cases are plotted in Figure 2 since we find no outgassing for the low case because the volatile content of the post-overturn mantle is vanishingly small.

Discussion & Conclusion: In the absence of any volatile delivery and outgassing (i.e. in the low case discussed above) the population of late impactors inferred from the lunar cratering record are able to erode

the entire current Earth's atmosphere (see Figure 1). However, for initial H_2O and CO_2 concentration in the mantle of about 0.05 wt% and more (medium and high cases discussed above and shown in Figure 2) the late impacts will lead to a net increase in Earth's atmospheric mass due to impact triggered outgassing (see Figure 2 and 3). Therefore, whether or not the Earth's atmosphere is eroded or grown during the late accretion phase depends critically on the initial volatile content of the mantle at the end of the magna ocean phase after the last giant impact.

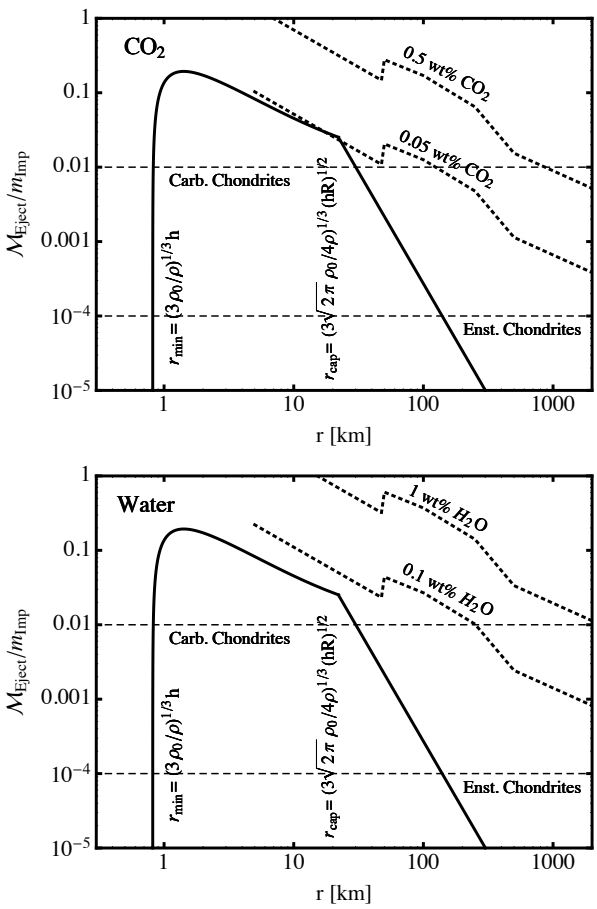

Figure 2: Volatile delivery and atmospheric erosion due to planetesimal/asteroid impacts. The solid line corresponds to the ratio of the atmospheric mass ejected to the impactor mass, M_{Eject}/m_{Imp}, and is plotted as a function of impactor radius, r, scaled to values corresponding to the current Earth's atmosphere (see [1] for details). r_{min} and r_{cap} refer to the minimum impactor size that can eject any atmosphere and the smallest impactor size that can eject the entire atmosphere above the tangent plane of the impact site, respectively. The dotted lines correspond to the amount of outgassing resulting from planetesimal/asteroid impacts for CO_2 (top) and H_2O (bottom) panel for different assumptions about the volatile budget of the mantle (see text for details). The dashed horizontal lines represent the volatile fractions of carbonaceous chondrites and enstatite chondrites.

If Earth's initial atmosphere was more massive in the past, then higher initial volatile concentrations in the mantle are needed to achieve atmospheric growth rather than erosion. This suggests that Earth's initial atmosphere may have been set by equilibrium between atmospheric erosion and outgassing during the late accretion phase.

Finally, the evolution of the atmosphere due to erosion by impacts is relatively smooth in time because the smaller impactors dominate it. The outgassing on the other hand (if conditions are such that it occurs) exhibits a very stochastic behavior as shown in Figure 3, because it is dominated by a small number of large planetesimal/asteroid impacts.

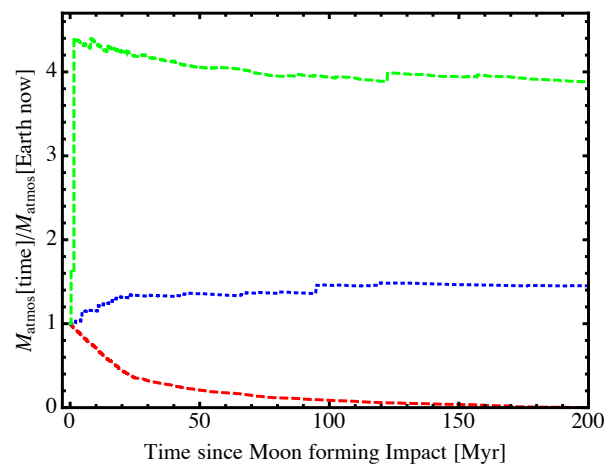

Figure 3: Example of Earth's atmospheric evolution due to its late accretion. The red dashed line is the same as in Figure 1 corresponding to atmospheric erosion in the absence of any outgassing, the blue dotted line and green dashed line both correspond to possible atmospheric evolution scenarios for impact triggered CO_2 outgassing assuming 0.05 wt% initial CO_2 (medium case discussed in text). The difference between the blue and green evolution scenarios is mainly due to a single large 1800km-radius impactor in Earth's bombardment history that is present in the evolution represented by the green curve and that is absent from the blue one.

References: [1] Schlichting et al. (2015), *Icarus,* 247, 81-94. [2] Marchi et al. (2014), *Nature,* 511, 578-582. [3] Marchi et al. (2016), *Earth and Planetary Science Letters*, 449, 90-104. [4] Neukum et al. (2001), *Space Sci. Rev.*, 96, 55–86. [5] Shuvalov, V. (2009), *Meteoritics and Planetary Science,* 44, 1095–1105. [6] Elkins-Tanton, L. T. (2012), *Annual Review of Earth and Planetary Sciences,* 40, 113-139