Terrestrial Atmospheric Erosion by Giant Impacts

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Introduction: Terrestrial planets form from tens of roughly Mars-sized embryos that crash into each other after accreting from a proto-planetary disk. At the same time, planets grow their atmospheres by accreting from their surroundings and by outgassing from their interior [1]. For a young atmosphere to survive, it must withstand radiation pressure of its host star, frequent impacts of small and medium impactors, and typically at least one late giant impact which could remove an entire atmosphere in a single blow [2]. In this study, we focus on the direct, mechanical consequences of giant impacts onto planets like the early Earth.

Our own planet is the perfect example, since we can both observe an atmosphere that has survived to the present day and be confident that a giant impact took place late in its evolution – creating the Moon in the process. Furthermore, the Earth's volatile abundances are remarkably different from those of chondrites [3]. Specifically, nitrogen and carbon are depleted compared with hydrogen, which could correspond to losing N_2 and CO_2 with an eroded atmosphere while retaining H_2O in an ocean [2]. The relative abundances of helium and neon in different-aged mantle reservoirs also suggest the Earth lost its atmosphere on at least two occasions [4].

Previous studies of giant-impact erosion have used analytical approaches and 1D simulations to estimate atmospheric loss [5, 6]. The 1D nature of these studies also means that little work has been done on grazing collisions, in spite of the fact that these are more likely to occur. The typical approach for giant impacts is to estimate the ground velocities induced by the impact to study how much atmosphere is blown away. This misses out the complex details of a collision that can violently mix, deform, and remake both an atmosphere and core. Any precise study of the consequences of a giant impact therefore requires full 3D modelling of the planet and atmosphere at the same time [7].

Giant impacts are most commonly studied using smoothed particle hydrodynamics (SPH) simulations, where planets are modelled with particles that evolve under gravity and material pressure. Standard simulations today use 10^5–10^6 particles, which is far too low resolution to include a thin atmosphere on top of a planet. In addition, the importance of improving resolution was demonstrated by Hosono et al. [8]. Simulations that gave apparently reliable results with up to 10^6 particles had not actually converged when re-tested with 10^7–10^8.

Computational advances have now allowed us to study the erosion of thin atmospheres with full, 3D simulations [7]. We ran high-resolution simulations of giant impacts with a variety of impact angles and speeds onto the proto-Earth, hosting a range of atmosphere masses. We study the detailed mechanisms of erosion, present a simple estimate for the fraction of lost atmosphere and discuss the implications for the Earth's volatile history.

Methods: As a recognisable starting point, we consider an impact similar to a canonical Moon-forming scenario, with a target proto-Earth of mass 0.887 $M_\oplus$ and impactor of 0.133 $M_\oplus$. Both are differentiated into an iron core and rocky mantle, constituting 30% and 70% of the total mass, respectively. We use the simple Tillotson iron and granite equations of state (EoS) for these materials [7]. For the atmospheres, we use Hubbard & MacFarlane (1980)'s H–He EoS [7]. The atmospheres are adiabatic, above a 500 K surface, while the inner layers follow a simple temperature–density $T \propto \rho^2$, that gives a core temperature of ~5000 K similar to the Earth today.

Using our open-source code SWIFT [7], we ran a primary suite of 74 simulations with $\sim 10^7$ SPH particles, plus 10 of these scenarios re-simulated additionally with 10^6, $10^{6.5}$, $10^{7.5}$, and 10^8 particles for convergence tests. We tested a range of atmosphere masses on the proto-Earth, namely 10^{-1}, $10^{-1.5}$, 10^{-2}, and $10^{-2.5}$ $M_\oplus$, ten impact parameters from 0 to 0.9, and up to eleven speeds from 0.75 to 8 times the mutual escape speed, v_esc. Fig. 1 shows a mid-collision example at 45° with 3 v_esc.

Atmospheric Erosion: The impact scenarios in the suite range from slow, head-on cases where the impactor merges with the target, to fast, grazing collisions where it escapes. In addition to the differences in the resulting fraction of lost atmosphere, the timing and cause

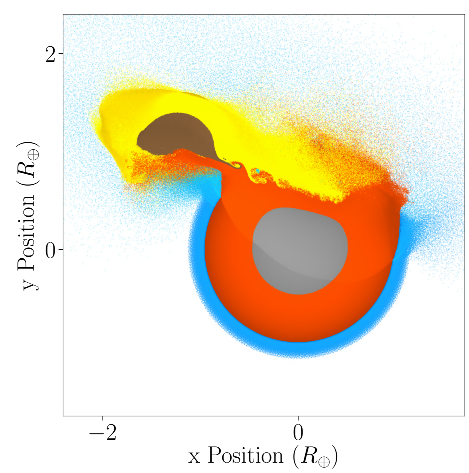

Figure 1: An example cross-section snapshot from a grazing collision simulated with 10^8 SPH particles, >100× higher resolution than the current standard. Grey and orange show the target's core and mantle material respectively, and brown and yellow show the same for the impactor. Blue is the target's atmosphere. The plotted luminosity varies with the internal energy, highlighting the shock wave created by the impact.

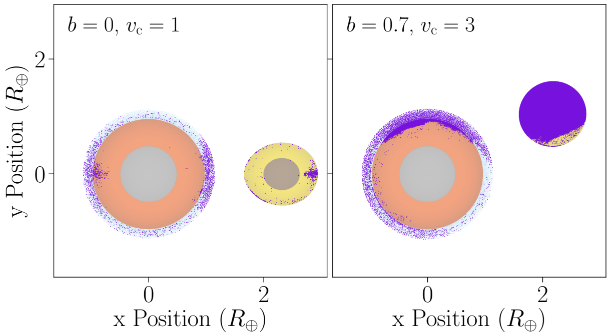

Figure 2: The particles that will become unbound and escape, highlighted in purple on a pre-impact snapshot for a slow, head-on and a fast, grazing collision. The impactors were travelling in the $-x$ direction at the moment they contacted the target. $b = \sin(\beta)$ is the impact parameter, where β is the angle at contact, and v_c is the speed at contact in units of the mutual escape speed. Only a thin slice of particles are shown for clarity.

of loss can also vary significantly. For example, atmosphere may be eroded by: direct encounter with the impactor passing through; shock waves travelling through the planet from the impact point; subsequent oscillations of the planet; and the secondary impact of the impactor following an initial grazing collision. All of these mechanisms may contribute to the total loss in a given scenario and illustrate the complexity created by all these processes intermingling.

Fig. 2 highlights the particles that are eroded by two example impacts, selected by being gravitationally unbound and remaining so until the end of the 10^5 s simulation. The first case shows loss around the impact point and antipode caused by direct contact with the impactor and later sloshing of the planet, though little global erosion from the shock wave. The second example shows both more atmosphere removed in the path of the grazing impactor and a stronger shock from the faster collision, while the impactor itself also escapes as a hit-and-run.

We also study the time at which erosion occurs. In all scenarios, the majority of loss has finished by 4–8 hours after contact. For impact speeds of $\sim$2 $v_{\rm esc}$ or greater, the erosion is completed almost immediately, with little change after only the first couple of hours. For low impact parameters, this is simply because the entire atmosphere is blown away by the initial shock. For grazing collisions, it is the lack of re-impacting fragments that reduces any later erosion.

Simple estimates of shock wave propagation from a point impact [6] significantly underestimate the ground speeds away from the impact point. So, combining them with 1D predictions of local erosion [5] produces inaccurate estimates of the global loss. However, if we use the peak ground speeds taken directly from our simulations, then the 1D estimates provide much closer predictions to the simulated loss results, both locally and globally.

In spite of the complicated details, including significant non-monotonic dependence on the angle at low

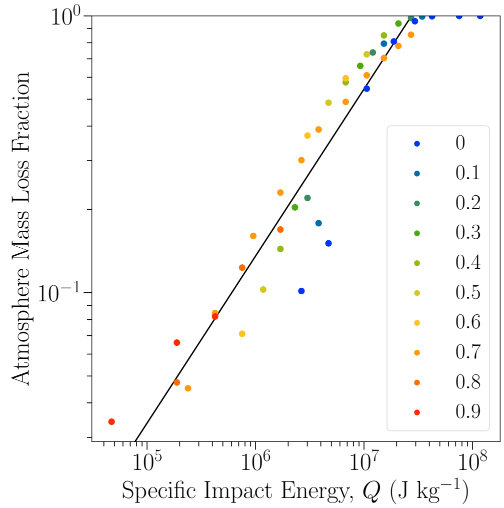

Figure 3: The lost mass fraction of the atmosphere for all the simulation scenarios as a function of their modified specific impact energy, coloured by their impact parameter. The black line shows the power-law fit to the data with <99% loss.

speeds, a single parameter can be used to estimate the erosion from any scenario. Fig. 3 shows the fraction of atmosphere lost as a function of the modified specific impact energy, based on the specific energy used by [10] to predict disruption. We find empirically that an additional factor of $(1-b)^2$ broadly accounts for the variation across the full range of angles: $Q = (1-b)^2 \, \frac{1}{2} \, \mu_{\rm r} \, v_{\rm c}^2 \, / \, M_{\rm tot}$, where $\mu_{\rm r}$ is the reduced mass. This allows a simple power-law fit to be made, as shown in Fig. 3:

$$X \approx 3.2 \times 10^{-5} \, \left(Q \, / \, \mathrm{J\,kg^{-1}} \right)^{0.603} \; . \qquad (1)$$

Note that the effects of changing the impact angle will have an additional dependence on the impactor mass which should be tested in future studies, perhaps provided by the $(1 - M_i/M_t)$ factor suggested by [11].

Conclusions: Using high-resolution simulations of giant impacts onto Earth-like planets with thin atmospheres, we examined the complex mechanisms by which atmosphere can be eroded and found a simple estimate for the fraction lost for any impact angle and speed. In the canonical Moon-forming impact, only around 10% of the atmosphere would have been lost from the immediate effects of the collision, although more could be removed in the presence of an ocean and during the resulting longer-term evolution [5].

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