



How reduced can post-impact terrestrial atmospheres be?

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Abstract

Giant impacts have been suggested as promising scenarios under which reduced species important to prebiotic chemistry can form (e.g., CH₄, NH₃, HCN, PH₃). This scenario relies on the ability of the impactor iron core to chemically reduce the planet's H₂O inventory, producing significant quantities of H₂ gas. Previous studies have focussed solely on the internal atmospheric chemistry of this process [1, 2]. The influence of the impact-generated melt phase on the atmospheric composition has been neglected. Further, the impactor's iron inventory has been assumed to be fully available to reduce the atmosphere. Here, we examine the effects of these two assumptions, and hence the ability of giant impacts to produce atmospheres suitable for subsequent prebiotic chemistry.

Method

We evolve our systems, comprised of a target and impactor, from their pre-impact states to a post-impact state prior to interactions between the melt and atmosphere (Figure 1). Impactors have a mass ratio of iron core to silicate mantle of approximately 30:70. A range of impactor masses are considered, although a typical mass of 2×10^{22} kg can be defined based off of Earth's mantle excesses in highly siderophilic elements [3]. The target has a pre-impact atmosphere of 100 bars CO₂ and 2 bars N₂, and a surface ocean of 1.85 Earth Oceans, considering estimates for early Earth. The target mantle oxygen fugacity is at the fayalite-magnetite-quartz buffer. As a result of the impact, the target's initial atmosphere is eroded, its oceans are vaporised, and its surface is partially melted. The iron core of the impactor breaks up [4], and is either accreted by the target or escapes the system. Iron made available to the atmosphere during this accretion acts to reduce the vaporised oceans and form H₂.

To calculate the silicate melt mass produced from impact, we use the iSALE shock physics code [5, and references therein]. Impact melt masses are determined and parametrised as a function of specific impact energy (Figure 2). To calculate the distribution of impactor iron, we use the GADGET2 smooth particle hydrodynamics code [6]. The distribution of the impactor iron (between the atmosphere, the mantle, and escaping the system) is determined and parametrised as a

function of impactor mass, impact velocity, and impact angle (Figure 3, see also [7]).

After impact processing, we evolve our system to equilibrium via melt-atmosphere interactions. We define equilibrium as when both the oxygen fugacities of the atmosphere and melt phase, and simultaneously the partial pressure of H₂O in each phase, are equal. Melt-atmosphere interactions include redox chemistry in an H₂-H₂O-Fe₂O₃-FeO-Fe system, and water partitioning between the atmosphere and the melt phase.

Results

We find that for larger impactor masses, both the inclusion of the impact-generated melt phase and the iron distribution individually act to decrease the abundance of H₂ in the post-impact atmosphere. Together, their effects compound one another to produce a large decrease in H₂ compared to the fiducial case without either effect. This change holds over a range of initial conditions.

We find that the greatest change is caused by the presence of the melt phase. Interactions between the atmosphere and melt phase alone (i.e., following previous models' assumptions of all impactor iron being available to reduce the atmosphere [1]) can decrease the atmospheric H₂ abundance by up to an order of magnitude, with greater change at greater impactor masses (Figure 4, left).

The distribution of the impactor's iron affects results in 2 ways. Firstly, some of the reducing power of the impactor is lost, either through iron being buried in regions of the mantle not able to take part in melt-atmosphere interactions (e.g., solid mantle or rapidly solidifying melt), or through iron escaping the system during breakup of the impactor. Secondly, at large impactor masses, the reduction of the atmosphere by the impactor iron leads to a mass loss from the atmosphere that decreases atmospheric pressure. The decreased system pressure then influences the oxygen fugacity of the melt phase and affects the partitioning of H₂O, both of which affect the H₂ abundance of the atmosphere at equilibrium. These effects can further decrease the atmospheric H₂ by up to a factor of 3 (Figure 4, right).

Conclusions

Including equilibration between the impact-processed atmosphere and the impact-generated melt phase, as well as distribution of the impactor's iron inventory, can decrease atmospheric H₂ by up to an order of magnitude compared to the fiducial model not considering these effects. Overestimated H₂ abundances can produce atmospheres suitable for subsequent formation of reduced species important for prebiotic chemistry. However, these atmospheres are also problematic for prebiotic chemistry in terms of surface temperatures and the blocking of Solar UV radiation by reduced carbon species in the atmosphere.

Atmospheres that are in equilibrium with the impact-generated melt phases below them, and that have been formed under distribution of the impactor iron inventory, are more oxidised and less massive than the fiducial case without either effect. These atmospheres are thus less likely to encounter issues surrounding surface temperature and UV blocking. Importantly, despite the decreases in H₂ from the fiducial case, these atmospheres still host H₂ abundances sufficient for subsequent prebiotic chemistry to take place.

References

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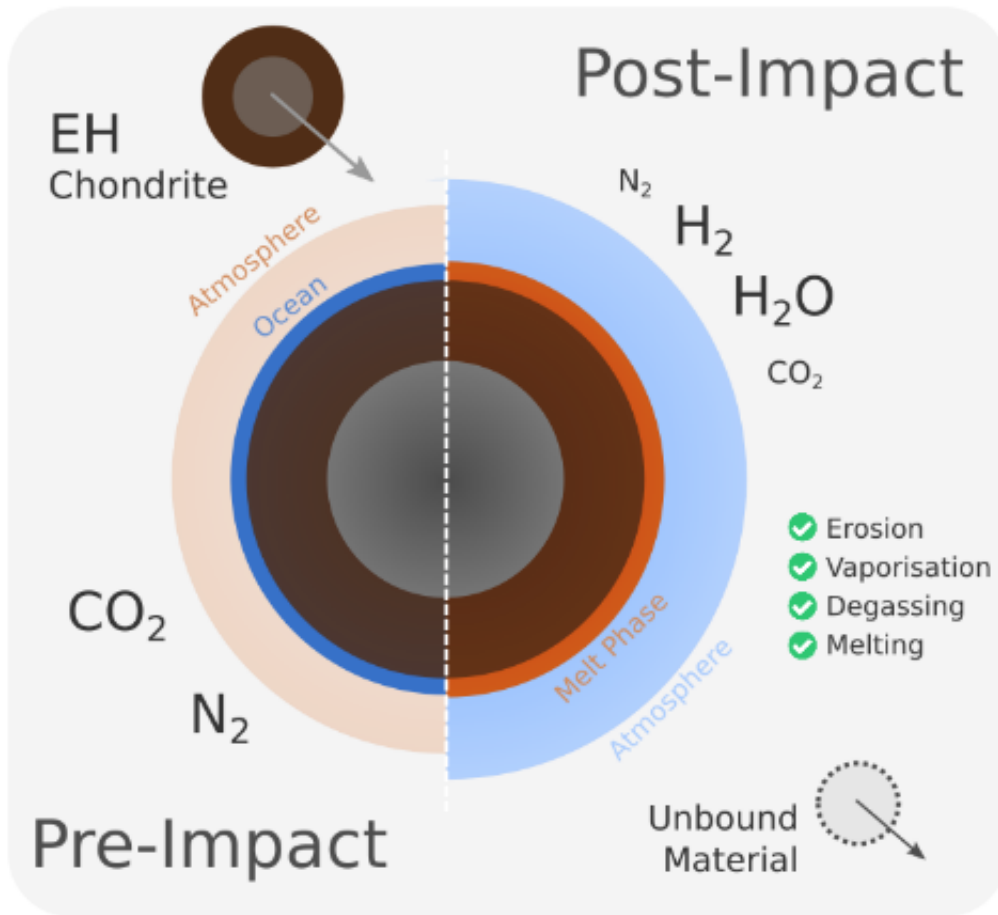


Figure 1: Processing of the target and impactor from their pre-impact states, through impact processing, to their post-impact states, from which melt-atmosphere interactions can begin. Processing includes the eroding of the pre-impact atmosphere, vaporisation of the surface oceans, melting of the target mantle, and reduction of the vaporised oceans by the impactor's broken up iron core.

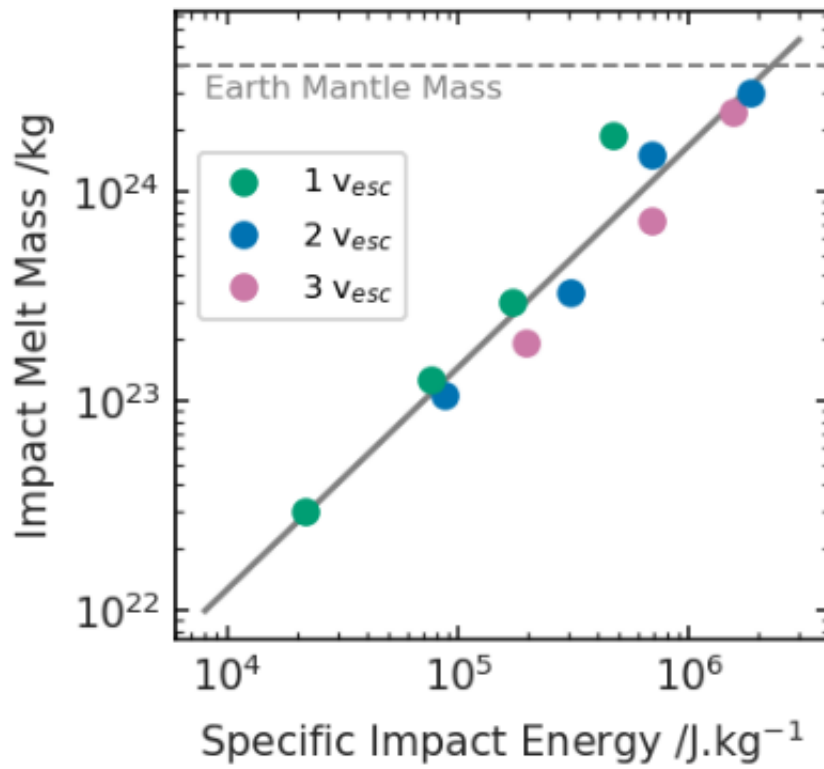


Figure 2: Impact-generated melt masses from iSALE simulations for a suite of impactor masses and impact velocities.

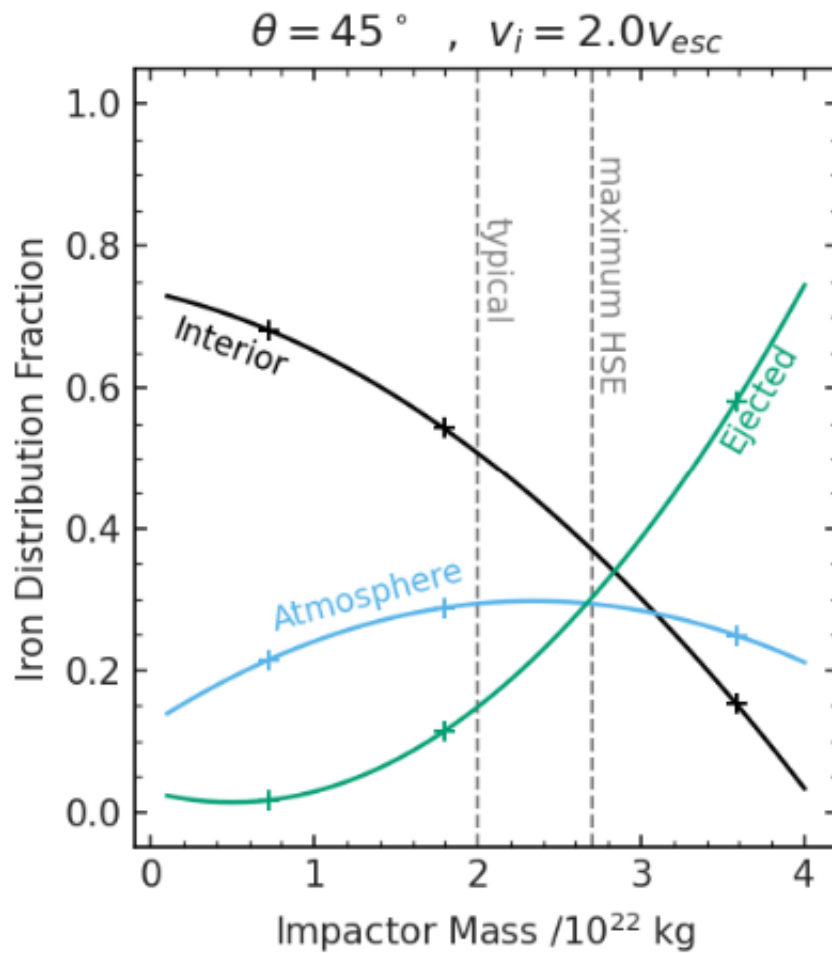


Figure 3: Distribution of the impactor's iron inventory from GADGET2 simulations for a range of impactor masses using typical values of 45° impact angle and impact velocity of 2 Earth escape velocities (~ 22 km/s).

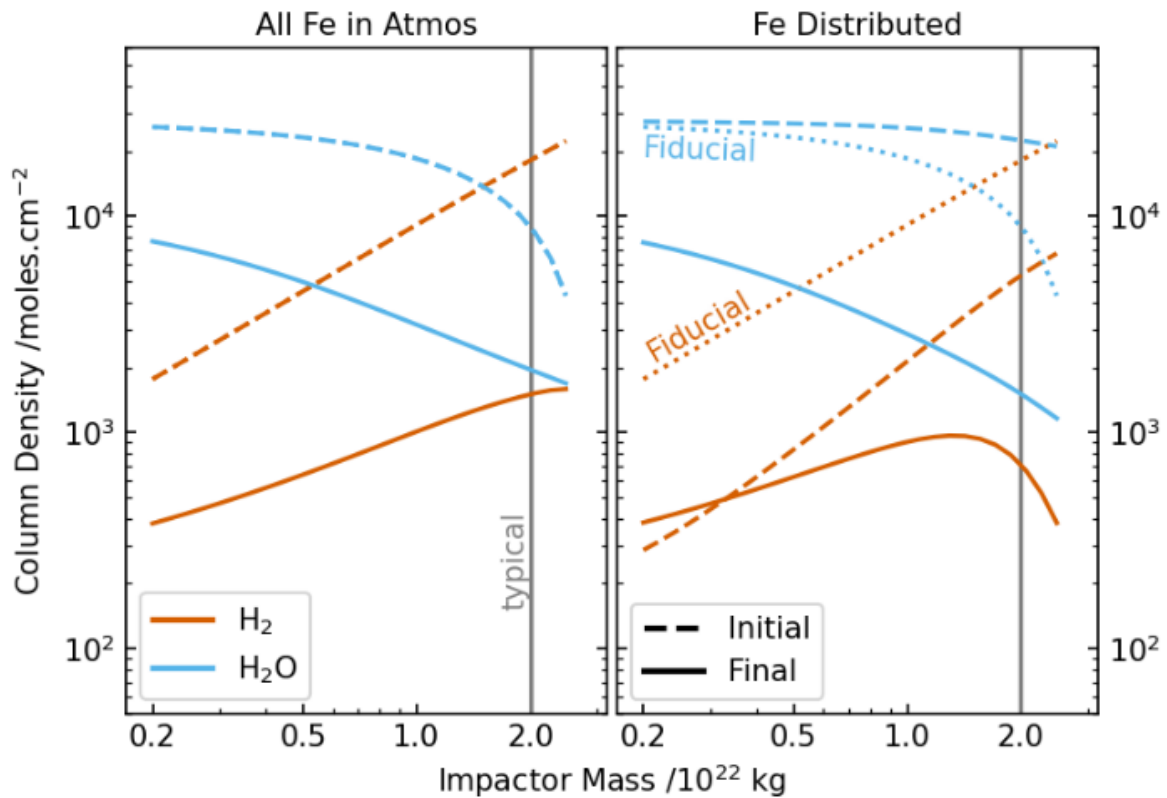


Figure 4: Comparison of atmospheric compositions under different modelling scenarios. Dashed lines represent the initial composition of the atmosphere, after impact processing but before any melt-atmosphere interactions have taken place. The solid lines show the composition after such interactions. The dotted lines represent the composition of the atmosphere in the base case, where no interactions are considered, and the impactor iron is all available to reduce the atmosphere. (*Left*) the impactor iron is fully available to the atmosphere. As such, the initial atmospheric composition mirrors that of the base case. The final composition thus shows the effect of melt-atmosphere interactions in isolation. (*Right*) the impactor iron is distributed between the atmosphere, the mantle, and escaping the system. The initial atmospheric composition is thus different to the base case. The final composition shows the compounding effects of both melt-atmosphere interactions and iron distribution.