ATMOSPHERIC LOSS IN GIANT IMPACTS DEPENDS ON PRE-IMPACT SURFACE CONDITIONS.

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Introduction: How Earth acquired its unique atmosphere and ocean is a fundamental question. Earth is thought to have gained a large fraction of its current budget of highly volatile elements (e.g., N, C, H, noble gases) during the main stages of accretion [1,2]. Planet formation is a violent, stochastic process and the volatile budget of Earth was shaped by the many mechanisms acting during accretion by which planets, and their building blocks, can gain and lose volatiles [e.g., 3-8].

Giant impacts, collisions between planet-sized bodies, could potentially play a significant role in the loss and gain of volatiles from terrestrial planets [4-8]. Most planets experience several giant impacts during their formation [e.g., 9] and they are the highest energy events planets experience. Giant impacts have a particular significance for Earth as the last impact injected material into orbit, forming our Moon [10,11].

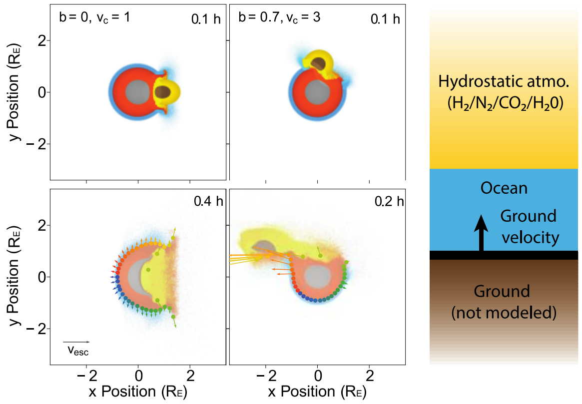

Figure 1 | Left: Two giant impact simulations from [8] showing the colliding bodies shortly after first contact (top) and upon breakout of the impact shock wave (bottom). Arrows show the peak velocity of the surface. Right: Schematic of a 1D loss simulation.

Only a fraction of the volatile budgets of the colliding bodies is inherited by the final post-impact body. Close to the point of collision, atmosphere/ocean is removed as part of melt and vapor plumes (Fig 1). Further from the impact site, atmosphere can be lost by breakout of the shock wave from the impact at the surface of the planet. Previous studies have either calculated the atmospheric/ocean loss using 1D calculations of ejection due to the ground motion caused by the impact shock wave [5-7], or by direct calculation of the loss of thicker atmospheres in 3D hydrodynamic giant impact simulations [8, 12]. These two approaches are limited in different ways. 1D simulations are unable to capture the full complexity of giant impacts, whereas 3D simulations are limited by computational expense and numerical resolution to considering a limited range of surface conditions and atmospheres that are much more massive than those of the current terrestrial planets. Importantly, previous studies have considered only a limited range of surface conditions (atmospheric pressure, temperature, composition etc.).

Here we use a suite of 1D hydrodynamic simulations to quantify the effect that pre-impact surface conditions (such as atmospheric pressure and presence of an ocean) have on the efficiency of atmospheric and ocean loss from proto-planets during giant impacts. Future work will combine our results with 3D impact simulations to develop scaling laws for atmospheric loss.

Methods: To calculate atmospheric and ocean loss due to ground motion we follow a similar approach to that of [5,6]. A hydrostatic atmosphere, and in many cases a hydrostatic ocean, is initialized at the radius of the planetary surface in a 1D spherical geometry. The breakout of the shock wave is then simulated by giving the lower boundary a vertical velocity that generates a shock wave in the atmosphere (and ocean) that accelerates a fraction of the atmosphere (and ocean) to escape (Fig 1). To perform our 1D simulations we have adapted the 1D WONDY hydrodynamic code [13]. WONDY solves the Lagrangian 1D mass, momentum and energy equations using a finite difference method.

We ran loss simulations for a wide variety of surface pressures (0.1-900 bar), surface temperatures (273-2000 K), atmospheric compositions (CO_2, N_2, H_2O, H_2), ocean depths (0.1-30 km), planetary masses (Mars-Earth), ground velocities, and using the three different equations of state (EOS) for water to explore the dependence of each of these parameters on the efficiency of loss. All gases were modeled as ideal. We used the results of these simulations to construct a scaling law that describes the fraction of loss for a given ground velocity and surface conditions.

This approach does not directly account for the fact that for a given strength of impact shock (which we describe by the particle velocity of the shock in the planet before release to the atmosphere/ocean) the ground velocity itself is dependent on the surface conditions. Previous 1D studies have not calculated this effect. To determine the relation between the strength of shock and the ground velocity we used a 1D impedance match solution. Loss was then calculated by convolving the impedance match velocity with our parameterization for loss as a function of ground velocity. Future work will directly simulate the shock in the planet.

Results and discussion:

The case of no-atmosphere. Our results agree well with previous studies. We find that the relation between ground velocity and loss is insensitive to the properties of the atmosphere. However, the dependence of ground velocity on the atmospheric properties means that lighter, hotter, and lower-pressure atmospheres are more easily lost (Fig 2).

Planets with oceans. Our results agree with those of previous work at low ground velocities (<6kms^{-1}), but deviate at higher ground velocities due to use of improved EOS for water. The presence of an ocean can significantly increase the efficiency of atmospheric loss for a given ground velocity compared to the no-ocean case. We find a rapid transition between low and high loss regimes largely controlled by the mass ratio of the ocean and atmosphere.

However, the higher impedance of an ocean can significantly decrease the ground velocity for a given strength of impact shock. Therefore, contrary to previous thinking, the presence of an ocean can also decrease loss if the ocean is not sufficiently massive to enter the high efficiency loss regime, which typically requires a few times the atmospheric mass (Fig 3).

Conclusions: Atmospheric and ocean loss due to giant impacts is highly sensitive to the surface conditions on the colliding bodies. In particular, we have shown that the impedance match between the planet and atmosphere/ocean plays a significant role in determining the efficiency of loss, an effect not quantified in previous studies. To allow our results to be combined with 3D impact simulations, we have developed scaling laws that relate the surface conditions and ground velocity to the efficiency of loss. Our results demonstrate that the final volatile budgets of planets are critically dependent on the exact timing and sequence of giant impacts experienced by their precursor planetary embryos, making atmospheric properties a highly stochastic outcome of planet formation.

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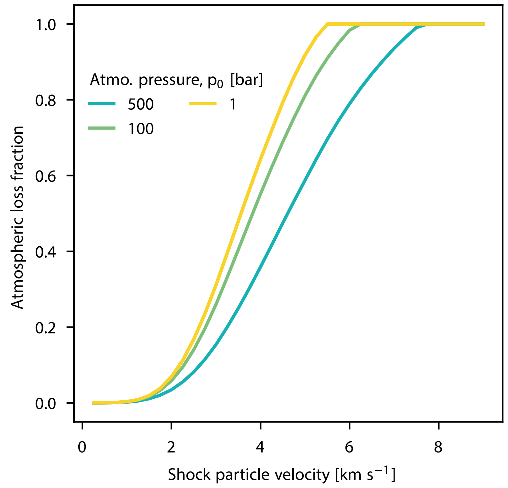

Figure 2 | The properties of the atmosphere influence the efficiency of loss in the no-ocean case due to the dependence of the ground velocity on the atmospheric temperature, pressure, and composition. Shown is the fraction of atmosphere lost from an Earth-mass planet due to an impact shock of a given particle velocity in the planet before release. Different lines show the results for CO_2 atmospheres with different pressures.

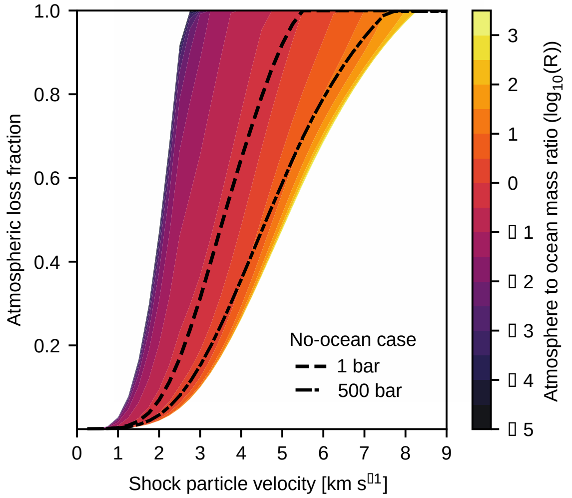

Figure 3 | The presence of an ocean can <u>increase or decrease</u> the efficiency of atmospheric loss. Shown is the fraction of atmosphere lost from an Earth-mass planet due to an impact shock of a given particle velocity in the planet before release to the ocean, for different atmospheric to ocean mass ratios (contours). The loss in the no-ocean case for two different atmospheric pressures are shown as black lines.