IMPACT–ATMOSPHERE–INTERIOR INTERACTIONS IN TERRESTRIAL PLANETS ON DIFFERENT TIMESCALES

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Introduction: In the early stage of their evolution, terrestrial planets are exposed to an intense bombardment of meteorites with different compositions and of a broad range of sizes. These meteorites interact with their targets in a variety of ways over a range of different timescales and influence the formation and evolution of their atmospheres. During the collision itself, the incoming impactor erodes a part of the atmosphere mechanically and may burst before reaching the solid surface if it cannot withstand the ram pressure; in this case, its intense heating will release its volatile content into the atmosphere and replenish it with volatiles, thereby modifying its composition. If it does hit the ground, it forms a crater and produces melts as a consequence of shock wave compression of the target. Further melt is formed by decompression when the crater is excavated and when the target material eventually is uplifted forming a central peak or ring(s) in the concluding stages of crater formation. These processes occur during the impact and its immediate aftermath, and the melt thus produced exchanges volatiles with the atmosphere mostly on a timescale of minutes to weeks or months, i.e., instantaneously by geological standards (Fig. 1).

Beyond these immediate effects, there are longer-term processes that continue to influence the evolution and composition of the atmosphere; we consider two of them. Firstly, the ejecta formed by the excavation of the crater and the extruded melts provide fresh surfaces that are suddenly exposed to the reactive volatiles of the atmosphere (and possibly hydrosphere). Their weathering draws CO_2 from the atmosphere over timescales of years to many millenia and sequesters it for long times in the interior. Secondly, larger impacts that penetrate to sublithospheric depths are expected to trigger local or regional magmatic activity that is fed by thermal upwellings caused by the shock heating of the target. The melts extruded as part of this magmatic activity exchange volatiles with the atmosphere on timescales of up to a few million years, depending on the magnitude of the impact.

Method: We constructed a system of parameterized representations of impact-related processes such as crater formation, atmospheric erosion, and impact melt production (e.g., [1, 2, 3, 4]) in order to model how impactors of different types and a large range of sizes could affect CO_2–H_2O atmospheres and interiors of terrestrial planets similar to Mars or Venus. Impactor-induced mass fluxes leading to, e.g., atmospheric escape, delivery and outgassing are calculated assuming CO_2–H_2O atmospheres in order to assess under which conditions atmospheres and interiors could be depleted or enriched by processes related to impacts and associated melting or weathering. By combining parameterized models of single impacts with statistical information about the impactor flux such as the size–frequency distribution of impactors and the cratering chronology, one can deduce evolutionary paths of the volatile contents of the atmosphere and, within limits, of the interior.

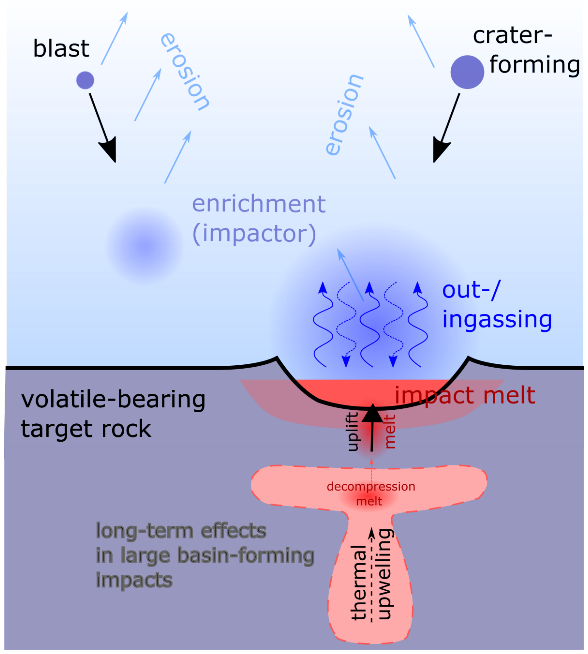

Figure 1: Schematic summary of modeled processes. A thermal upwelling causing long-term magmatism is expected only in impacts large enough to reach into the mantle.

These parameterizations of short-term processes are complemented by simple semi-analytical models of volatile exchange between the atmosphere and the solid planet that act on longer timescales, specifically weathering and magmatism induced by mantle convection. The volatile exchange between melts and the atmosphere is controlled by a simple solution model with atmospheric pressure as the principal control [5].

We consider rocky S-type and icy-rocky C-type asteroids as well as comets, covering a range of impactor–target density contrasts from about 1/6 to about 4/5 and a range of (absolute) impact velocities from a little less than 10 to almost 65 km/s. Impactor size ranges from 1 m to half the planetary radius. Atmospheric surface pressures cover almost five orders of magnitude, ranging from a few millibars (∼modern Mars) up to 95 bar (∼modern Venus). CO_2-dominated atmospheric compositions representative for modern-day Mars and Venus were assumed; other gases were not included.

With regard to atmospheric effects, there is a fundamental distinction to be made between blast-producing and crater-forming impacts; the boundary that separates these two regimes is mostly defined by the deceleration of the impactor and its resistance to breakup under the ram pressure during its traversal of the atmosphere. The direct effects of the former leave the interior essentially unaffected and interact only with the atmosphere. We use the formalisms by [4, 3, 6] to assess the bulk mass transfer and balance resulting from mechanical erosion of the atmosphere and the disintegration of the impactor and estimate the balance for the individual volatiles from estimates of the impactor composition. In crater-forming impacts, there are additional effects that need to be included. Ejecta can contribute to the mechanical erosion of the atmosphere (e.g., [3]) and also produce layers of porous material with a large, reactive surface that can absorb CO_2 from the atmosphere by weathering in the long-term aftermath of an impact. Moreover, they produce craters which facilitate the interior–atmosphere mass exchange.

Results: The immediate effects of an incoming meteorite are mostly mechanical, and the more volatile-rich but also faster comets cause stronger effects than asteroidal meteorites. In terms of atmospheric mass change normalized by impactor mass (impact efficiency), Mars' tenuous atmosphere is most efficiently eroded by small cometary impactors that cause only blasts, whereas asteroidal ones as well as large comets seem to result in net enrichment in most of the diameter range considered (Fig. 2). In Venus' thick atmosphere, erosion is generally less effective and becomes substantial only for much larger impactors. The differences between the impactor types are less pronounced in this case. Although large impactors erode the atmosphere more strongly in absolute terms, their erosive efficiency as measured in terms of their mass is less than that of smaller impactors over a wide range of size and across impact regime boundaries.

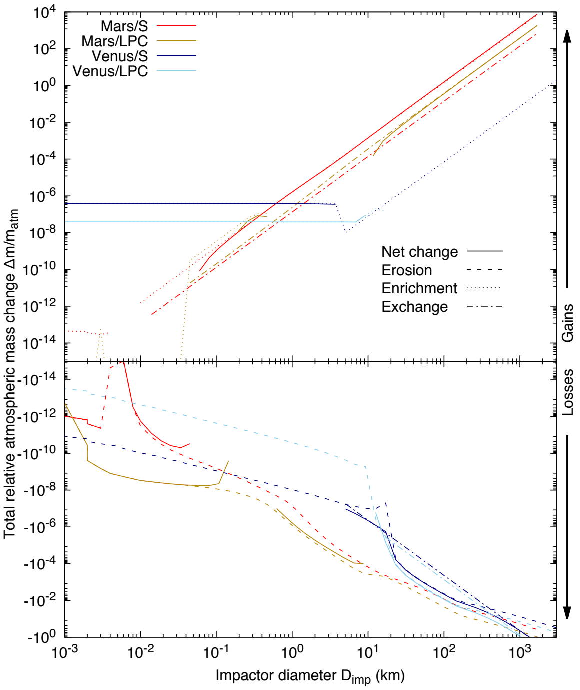

Figure 2: Total relative atmospheric mass change as a function of impactor size for rocky S-type asteroids and long-period comets (LPC) as impactors (solid curves). The individual atmospheric erosional and enrichment contributions as well as the volatile exchange between melt and atmosphere are also shown.

A key process with regard to atmosphere–interior exchange and longer-term consequences of an impact is the production of impact melt, which can serve as a vehicle for volatiles between the atmosphere and the interior by either releasing or dissolving CO_2 and water, depending mostly on the pressure conditions at the interface; generally outgassing is expected to be more common, but still the two volatiles may behave quite differently. Consistent with previous studies we find that CO_2 is expelled from the melt much more easily than H_2O and could therefore enter the atmosphere under all the conditions considered, whereas water may be retained in the melt at high atmospheric pressures. Comets are more efficient than asteroids in producing shock melts, but they must also be several times larger to produce a crater in the first place. Given their limited size, they are expected seldom to reach the ground on Venus.

CO_2 drawdown by weathering might have a substantial effect on the martian atmosphere; in theory (but probably not in practice) the ejecta of a single very large impact could take up the entire atmosphere. On Venus, weathering is less efficient, and even the ejecta of the largest impactors are not expected to have an absorption capacity of more than 10% of the atmospheric mass.

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References: [1] E. Pierazzo, et al. (1997) *Icarus* 127(2):408. [2] T. Ruedas (2017) *Icarus* 289:22. [3] V. Shuvalov, et al. (2014) *Planet Space Sci* 98:120. [4] V. V. Svetsov (2007) *Sol Syst Res* 41(1):28. [5] L. Parfitt, L. Wilson (2008) *Fundamentals of Physical Volcanology* Wiley–Blackwell. [6] J. Kegerreis, et al. (2020) *Astrophys J* 897(2):161.