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Temporal evolution of impact-atmosphere-interior interactions in terrestrial planets

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We constructed a system of parameterized or semi-analytical representations of impact-related processes such as crater formation, atmospheric erosion, and melt production due to the direct effects of the impact as well as the long-term thermal effects triggered in the mantle by very large impacts in order to model how impactors of different types and a large range of sizes affect the CO_2-H_2O atmosphere and the interior of a terrestrial planet similar to Mars, Venus, or the early Earth. Mass fluxes of carbon dioxide and water between the impactor/outer space, the atmosphere, and the interior of the target planet are calculated in order to assess under which conditions atmospheres and interiors are depleted or enriched by processes related to impacts, melting/magmatism on different time scales, or weathering.

The impactor flux onto a planetary target is a stochastic process in terms of time, magnitude and location, which we describe with a size-frequency distribution of impactors and a cratering chronology. The temporal aspect, in combination with the complexities of the various effects of a single impact, cause the evolution to depend on its own history. In the absence of unique information about the impact sequence of a target, the evolution should therefore not be uniquely determined by cratering statistics, and the possible paths are expected to vary within a certain range. Thus, we aim to deduce a range of evolutionary paths for the volatile content of the atmosphere and, within limits, of the interior.

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 as well as 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) densities cover almost five orders of magnitude, ranging from a few millibars (modern Mars) to 95 bar (modern Venus).

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 formalism by Svetsov (2007) 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., Shuvalov et al., 2014) 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 a crater that opens up the interior to mass exchange with the atmosphere. A key process in this context is the production of impact melt, which can serve as a vehicle for volatiles between the atmosphere and the interior by either releasing or removing (by dissolution) CO_2 and water, depending mostly on the pressure conditions at the interface; generally outgassing is expected to be more common, but still these two volatiles may behave quite differently. We find that CO_2 is expelled from the melt much more easily than water and will therefore enter the atmosphere under all conditions considered, whereas water may be retained in the melt at high atmospheric pressures. In addition to these common effects, very large impacts cause perturbations at sublithospheric depths and implant local thermal anomalies into the mantle that subsequently turn into upwellings and can cause longer-term magmatism and the local degassing from the deep interior.