Some effects of multiple large meteorite impacts on Mars

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Model setup

Most studies of the effect of basin-forming impacts on mantle convection include only a single impact. The actual evolution of planets, however, is shaped by a multitude of impacts, many of which occur in relatively close succession and proximity to each other, and so interactions between them are expected. We investigate the extent of mutual interaction between two or more impacts as a function of spatial and temporal separation with a series of numerical mantle convection models.

Our 2D models include a detailed description of mantle mineralogy and chemistry and consider core cooling (cf. Ruedas and Breuer, 2017). These models are combined with a parameterization of the effects of an impact built on the approach of Watters *et al.* (2009) and the pressure decay with distance from the impact center as given by the "inverse-r" parameterization from Ruedas (2017). In order to relate the spacing and timing of subsequent impacts to their magnitude, we scale the spacing Δx with the diameter of the isobaric core D_{ic} and the time Δt between impacts by an estimated decay time Δt_{d} for the dynamical effects of an impact in some models.

Model properties

All models: Initial potential temperature: 1700 K; initial T step across CMB: 150 K; 15fold viscosity increase between upper and lower part of mantle; radionuclide concentrations from Wänke and Dreibus (1994), Mg#=0.75, 36 wppm water; melting included, threshold for melt extraction: 0.7%; liquid Fe–S alloy core (16 wt.% S, $R_{\mathrm{c}} = 1730$ km), no basal bridgmanite+ferropericlase layer in the mantle; start: 4.5 Ga; S-type asteroid impactor, 2720 kg/m^3, 9.6 km/s, striking at an angle of 45°

Two-impact models: Utopia-sized (final crater diameter D_{f}: 3380 km, impactor diameter D_{imp}: 699 km) or Isidis-sized (D_{f}: 1352 km, D_{imp}: 244 km) impacts; first impact at 4 Ga, second $0.5\Delta t_{\mathrm{d}}$, Δt_{d}, or $2\Delta t_{\mathrm{d}}$ later at a distance of D_{ic}, $2D_{\mathrm{ic}}$, $5D_{\mathrm{ic}}$, or $10D_{\mathrm{ic}}$

Multiple-impact models: 4–8 basin-forming impacts with varying magnitudes ranging from Hematite (D_{f}: 1065 km, D_{imp}: 189 km) to Utopia. The six impact sequences comprise all events that lie approximately on one of six great circles (GC) (Fig. 4). Their ages are taken from Frey (2008).

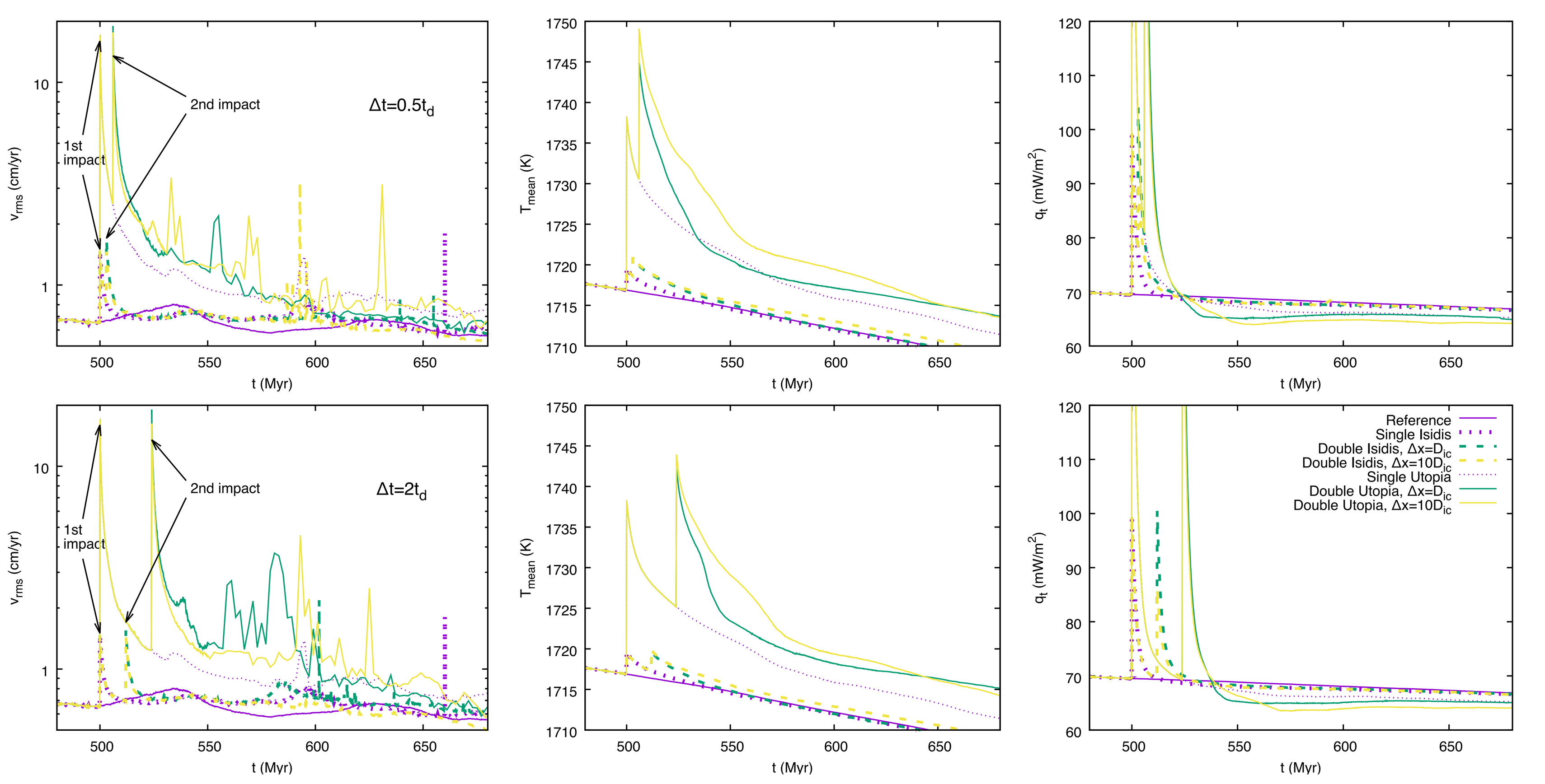

Fig. 1: Root-mean-square velocity v_{rms}, mean mantle temperature T_{mean}, and mean surface heat flow q_{t} for selected models with two impacts of either Isidis-like or Utopia-like magnitude and for the impact-free and the single-impact models. The Utopia models have been smoothed at $t > 530$–550 My by averaging over 2 My-intervals for better readability; the v_{rms} peaks at those times are due to lithospheric instabilities.

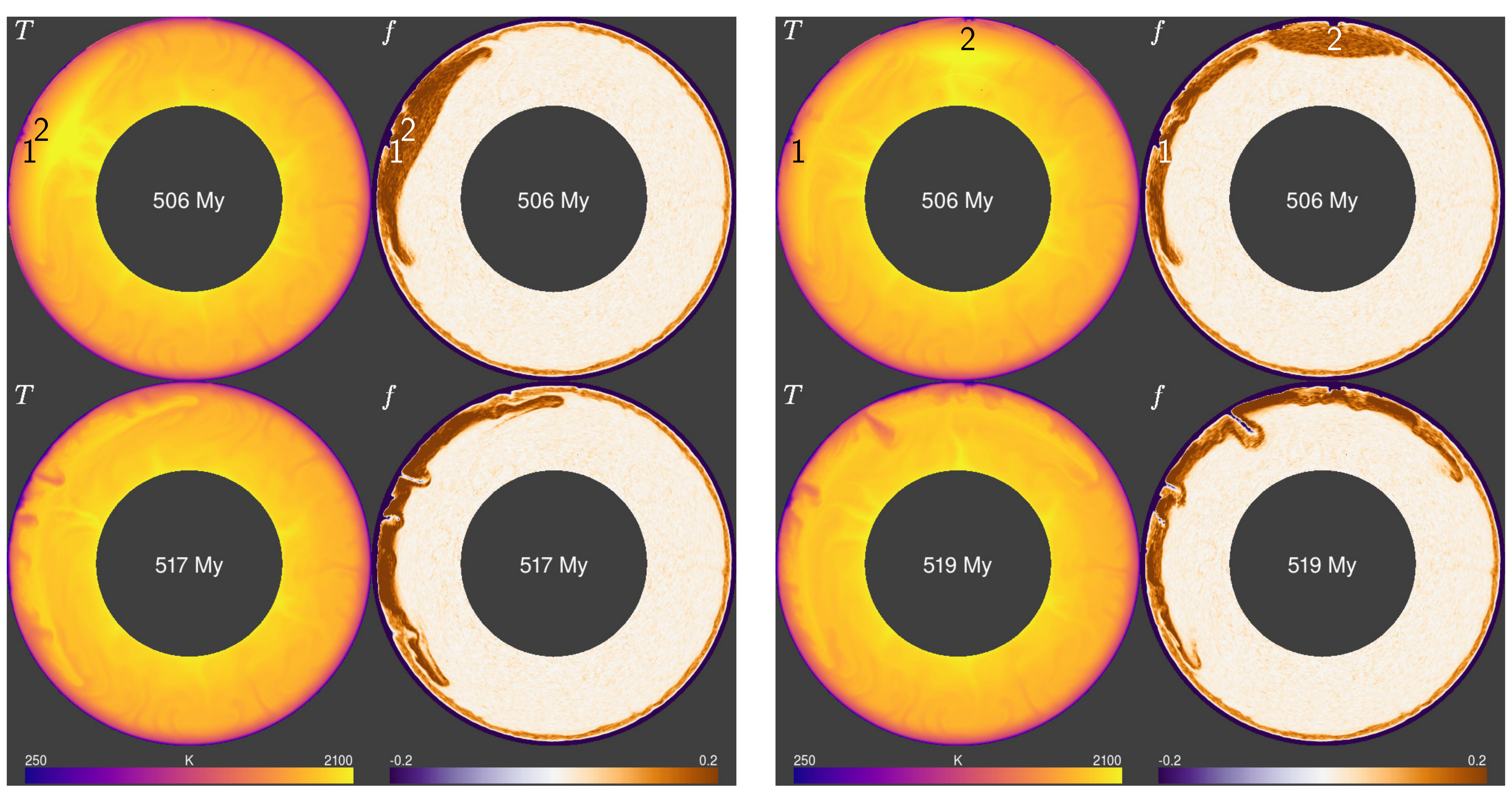

Fig. 2: Snapshots of temperature (T, left columns) and depletion (f, right columns) for the double-Utopia models with the closest and the widest Δx and the shortest Δt, taken just after the second impact. The impact sites are marked as "1" and "2" in the upper panels.

Results: Two-impact models

The sudden input of energy into the planetary interior by the impact produces a jump in several dynamical variables, e.g., the mean flow velocity v_{rms}, the mean mantle temperature T_{mean}, and the global mean surface heat flow q_{t}, followed by an initially steep decline (Fig. 1). The signal of the second impact is added to the decaying signature of the first in different ways for different variables.

The models show that

- the second impact peak in $v_{\mathrm{rms}}(t)$ tends to increase with decreasing Δx, because the lingering thermal anomaly from the first impact boosts the upwelling triggered by the second;
- the second $v_{\mathrm{rms}}(t)$ and $T_{\mathrm{mean}}(t)$ maxima are larger for smaller Δt, but the latter grow with Δx, because the total heated volume is larger in models with less overlap of the affected regions;
- the second q_{t} peak decreases with both increasing Δx and Δt, whereby the decrease with Δx is due to the deposition of cold material at the surface.

Melt production and extraction in the shock-heated volumes reduce their density, thus enhancing their buoyancy and reinforcing convection caused by impacts. This can also result in increased production of crust, but the extreme depletion of the shallower mantle in the impact-affected region counteracts this effect. As the impact-generated anomalies ascend and spread out beneath the lid, they may collide and merge after an initial stage of somewhat independent evolution. In cases with large Δx, a piece of normal mantle can get caught between them and induce a downwelling due to its relatively higher density, especially for smaller impacts with less vigorous dynamics (Fig. 2).

Results: Multiple impacts on a great circle

A succession of various different large impacts produces a strongly variable depletion pattern in the uppermost mantle (Fig. 3), but the vigorous post-impact dynamics and merging of individual anomalies precludes the distinction of clear boundaries between discrete events.

As in the two-impact models, thick crust is formed immediately after the impacts but partly delaminates on timescales on the order of 10^7 to 10^8 yr. However, the more perturbed dynamics of models with several impacts result in more extensive lithospheric instability in the later evolution, which in turn stirs the mantle up and enables prolonged melt and crust production in some places by transporting relatively fresh or re-enriched material into the melting zone. This leads to a second era of (limited and localized) crustal production considerable time after the last large impact that generates some sites of permanent thick crust if at least five or six basin-forming impacts on a great circle occur.

The lithospheric instability and subsequent transient accumulation of relatively cool material at the CMB also has potential implications for core dynamics. In most of these models q_{CMB} doubles for several hundred Myr after the impacts relative to the impact-free reference model (Fig. 5). The only exception, in which the increase is much less pronounced, is model GC5, which had only four impacts and was also the least productive in terms of post-impact crust formation.

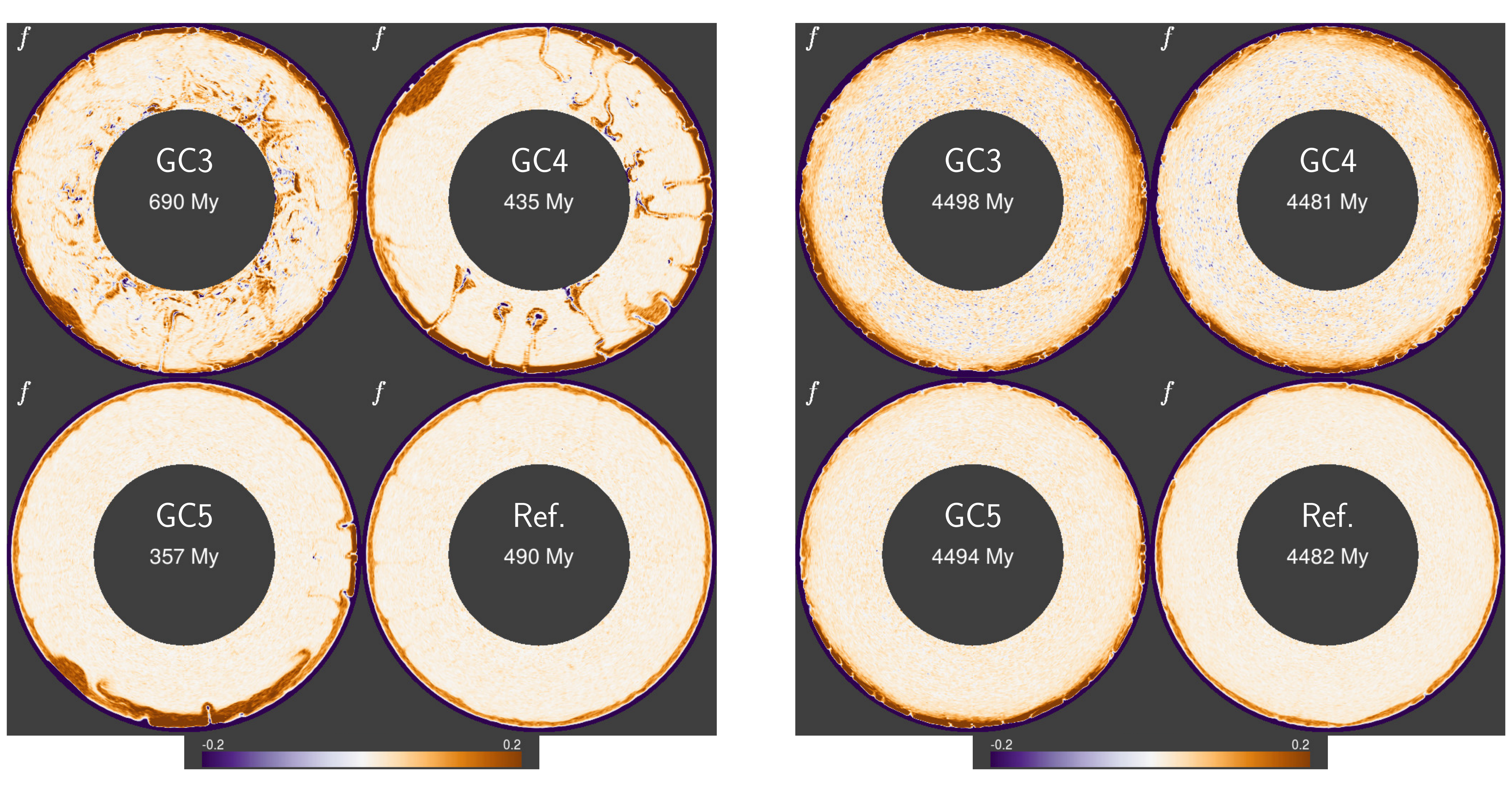

Fig. 3: Depletion for models GC3, GC4, GC5, and the impact-free reference model. Left block: after the last impact (GC models) or a similar stage (Ref.); right block: present-day.

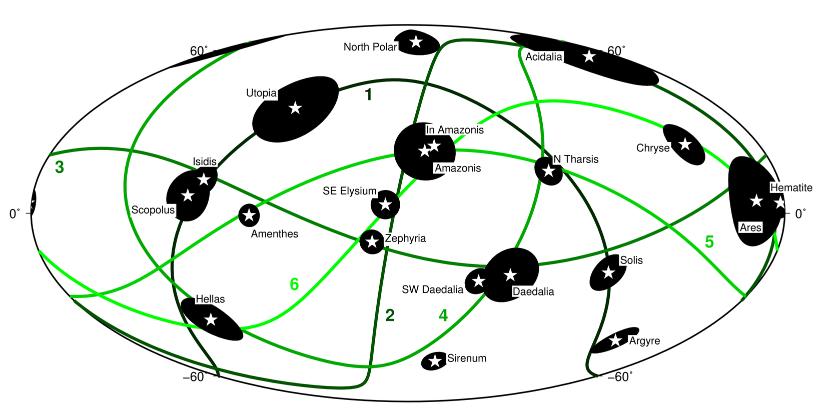

Fig. 4: Map of the locations of the large impact basins on Mars after Frey (2008) and the great circles (green curves) by which they are assigned to 2D models (green numbers).

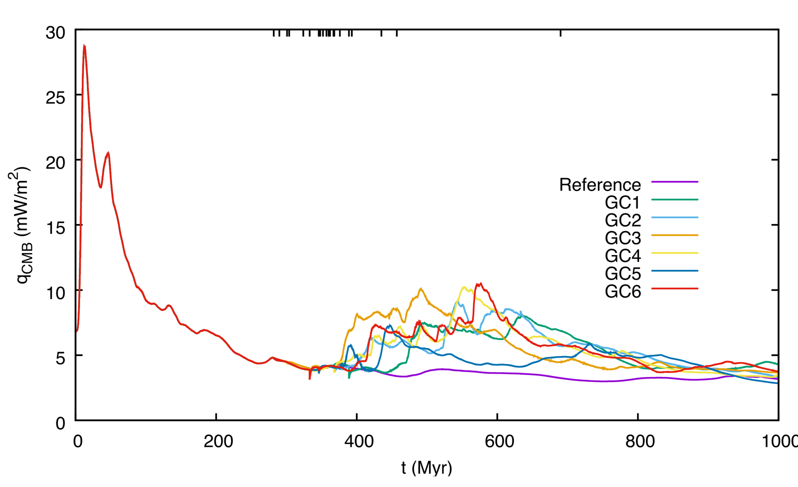

Fig. 5: CMB heat flow for the great-circle models during the first billion years. The ticmarks on the top abscissa mark the times at which impacts occurred in any of the models.

Summary

- Impacts are not isolated events but can influence each other via their dynamical effects. Very closely spaced impacts occurring shortly after one another can almost appear like a single larger impact, whereas the interaction is less direct and more complex as Δx and/or Δt grow.
- The differences between the models in the system's dynamical variables diminish with time, and the thermal impact signatures have disappeared long before the present. Compositional anomalies are preserved, but it is difficult to draw a sharp boundary between the region of influence of individual sufficiently closely spaced impacts. Variations in post-impact crust formation are also reflected in the crustal thickness.
- Very large impacts can trigger lithospheric instabilities that modify the convection flow field, and beyond some threshold these instabilities can become so extensive that they stir the mantle on a global scale and can reinforce crustal production. The accumulation of lithospheric material at the CMB may also have an effect on core dynamics.

Acknowledgments

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