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Electrical conductivity and seismic velocity of the martian mantle: signatures of large meteorite impacts

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Abstract

We revisit the results from numerical mantle convection models that were coupled with a petrological model of the martian mantle ([3]) and attempt to calculate electrical conductivity and seismic bulk velocity distributions.

1. Introduction

In the early stage of its evolution, Mars has experienced many very large meteorite impacts that left craters or basins as visible surface structures. These structures are often also associated with gravity and magnetic anomalies and identifiable on global maps. However, information derived from these data is ambiguous, but other geophysical methods, e.g., seismics and electromagnetic imaging has not yet been applied to such a target. We discuss the potential of electromagnetic and seismic observations for detecting or ascertaining impact structures, for clarifying the properties of their subsurface, and for the general characterization of the deep interior of Mars. The InSight seismometer and magnetometer may offer opportunities to test some of the predictions.

2. Method and models

The convection code is a modified version of StagYY [1] and solves the conservation equations of mass, momentum, and energy in the compressible, anelastic approximation with melting on a two-dimensional spherical annulus grid [2], using material properties from a petrological model ([3]). The impacts are represented as instantaneous thermal anomalies, with shock-heating derived from the peak shock pressure based on the impedance-match model (cf. [4]) and the pressure decay with distance from the impact center given by the "inverse-r" parameterization ([5]). We model the impacts after existing martian craters by deducing impact parameters such as the impactor size via scaling laws [6] from their observed diameters D_f.

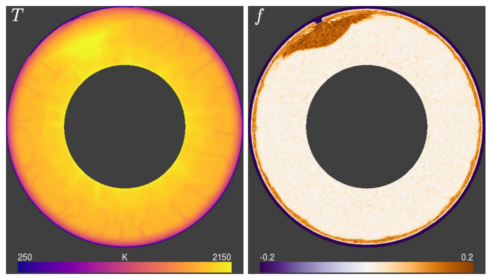

Figure 1: Temperature (left) and composition/depletion (right) at time of impact (4 Ga), for a Utopia-sized impact in a mantle with 36 ppm water.

The mineral composition and physical property information implemented in the petrological model along with additional mineral physics data is also used to derive the elastic parameters and the electrical conductivity of the minerals at the pressure, temperature, and composition at every grid point. The bulk rock properties are then determined using averaging schemes from effective medium theory and modified by a pressure-dependent porosity near the surface.

The general model parameters used in all models are listed in Table 1. There are four model sets with three models featuring initial bulk silicate water contents of 36, 72, or 144 ppm, respectively: except for the impact-free reference model set, the sets include a single impact at 4 Ga (400 My model time) with a size corresponding to the formation of the Huygens ($D_\mathrm{f} = 467.25$ km), the Isidis ($D_\mathrm{f} = 1352$ km), or the Utopia ($D_\mathrm{f} = 3380$ km) impact basin. The impactor is a rocky (S-type) asteroid hitting at 45° with the mean impact velocity for Mars.

3. Results

The impact generates an instantaneous disturbance in the crust and upper mantle in which the material has

Table 1: Important model parameters.

Mantle thickness	1659.5 km
Surface temperature	218 K
Initial potential temperature	1700 K
Bulk silicate Mars Mg#	0.75
Initial bulk water contents	36/72/144 ppm
Impactor density, ϱ_{imp}	2720 kg/m^3
Impactor velocity, v_{imp}	9.6 km/s

an anomalously low density due to the strong heating from the shock and the excessive loss of iron upon melting (Fig. 1). This volume rises quickly while producing further melt and spreads beneath the rejuvenated lithosphere. In the present, the thermal pulse has diffused away and flattened remnants of the compositional anomaly linger beneath the former impact site and its surroundings as parts of the lithospheric mantle, anchored there by their buoyancy and stabilized by the high viscosity of the lid (Fig. 2, top). The degree of preservation declines with increasing water content, because wetter mantle convects more vigorously.

The density anomalies $\Delta\varrho$ related to the impact do not exceed a few tens of kg/m^3 in the mantle but are an order of magnitude larger in the crust (Fig. 2). The magnitude of seismic anomalies can be estimated from calculated variations in the bulk sound speed $v_{\mathrm{B}} = \sqrt{K_S/\varrho}$ and rarely exceeds a few tens of m/s in the mantle but is again much larger in the crust due to the filling of pores (Fig. 2). For rays arriving at a station in the impact basin at a steep angle of incidence, runtimes shorter by several seconds compared to the global mean are predicted.

The electrical conductivity σ of the silicate part of Mars varies over several orders of magnitude from the surface to the CMB (Fig. 2) and is more sensitive to variations in water and iron content than other methods. Impact-related conductivity anomalies are predicted to be mostly negative (Fig. 2), which is mostly a consequence of above-average depletion in iron in the mantle and lower than average temperatures in the intra-basin crust, which has a lower concentration of heat-producing elements. Furthermore, the differences between models with different initial bulk water contents tend to be more pronounced than for other observables, and generally the sensitivity of σ with regard to compositional variations may offer a hitherto underappreciated opportunity to constrain the water content of the martian mantle, which is still a controversial issue.

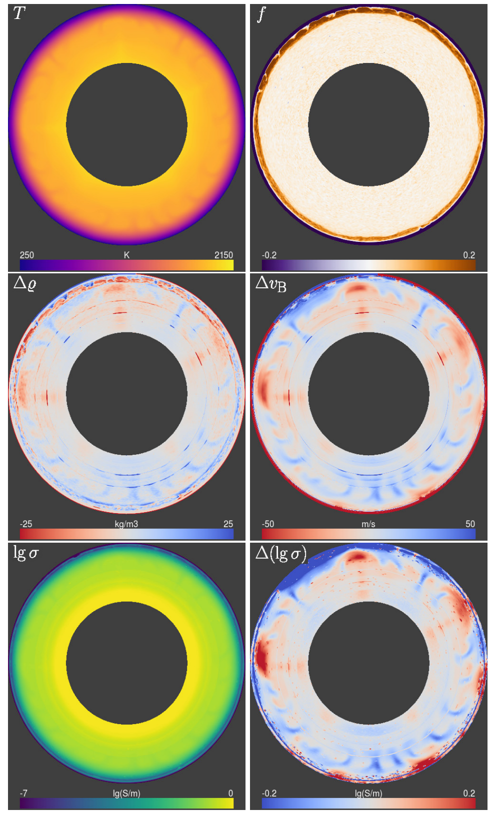

Figure 2: From left to right, top to bottom: Present-day temperature, composition/depletion, density anomaly, bulk sound speed anomaly, electrical conductivity and corresponding anomaly, for the impact of Fig. 1.

Acknowledgements

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