EPSC Abstracts
Vol. 12, EPSC2018-851, 2018
European Planetary Science Congress 2018

Synthetic geophysical observables from martian mantle convection models, with application to InSight

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Abstract

Fully dynamical convection models of the martian mantle coupled with a mineralogical model and a parameterized representation of a large meteorite impact are used to derive geophysical observables, in particular synthetic density/gravity, seismic velocities, and heat flow, which are of interest with respect to the ongoing InSight mission.

1. Introduction

We model the thermochemical evolution of Mars with the fully dynamical mantle convection code STAGYY [1] coupled to a petrological and mineral physics model of the mantle and core materials to determine their physical properties and melting behavior (cf. [2]). Starting at 4.4 Ga, the models are allowed to evolve undergoing compositional changes due to melting and are subjected to a large, basin-forming impact at 4 Ga that causes further melting and heating of the mantle and introduce major thermal and compositional anomalies. The impacts are implemented in a simplified, parameterized form that focuses on describing the first-order effects caused by shock-heating in the surroundings of the impact site (e.g., [3]). The final result of a typical modeling run is a model of the present-day thermal and compositional state of the martian interior, in particular of the mantle.

The coupling of the fluid-dynamical model to the mineral physics model ensures not only that the dynamical evolution is internally consistent with the thermoelastic properties of the mantle and core materials but also allows to derive various geophysical observables from the model in an internally consistent way. Some of the most important physical properties are the density, the seismic velocities, and the thermal conductivity, which are observed by gravity, seismics, and heat flow measurements from orbit or from the ground. Gravity measurements of Mars have been carried out by spacecraft for many years, whereas seismic and heat flow observations are expected to become available after 2018 with the deployment of the InSight lander now on its way to Mars.

2. Results

With time the planetary interior cools in all models. A depleted, less dense layer forms at the base of the lithosphere and reduces convective motion in the melting region. Impacts provide an instantaneous input of energy that temporarily disturbs this otherwise stable layering, the more the larger the impact. The strong thermal and compositional impact-generated anomalies (Fig. 1) spread out at the base of the lithosphere, where they leave a distinct signature in the density structure of the mantle that stabilizes compositional anomalies over long periods.

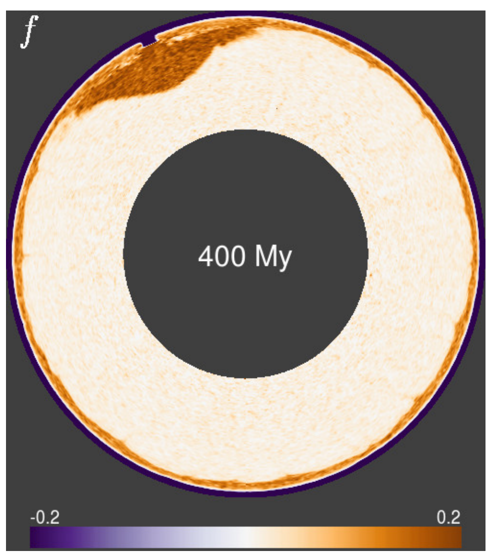

Figure 1: Compositional anomaly, Utopia-size impact.

The increased depletion caused by impacts modifies the density of the target and thus leaves a low-density mantle anomaly (Fig. 2a) that is expected to be visible in gravity measurements. Estimates show that the contributions of both the crust and the mantle to the total anomaly are detectable by ground-based and orbiting spacecraft and that neglecting the mantle anomaly may result in misestimates of the crustal thickness on the order of several kilometers.

Seismic velocity models of the mantle reproduce the expected first-order seismic discontinuities of the martian interior, including a mid-mantle discontinuity of ~ 210 m/s at a depth of about 1100 km that is mostly due to the high-pressure phase transitions of olivine; shallow, impact-generated anomalies (Fig. 2b), however, are too small to be detected with single stations such as the SEIS experiment of InSight or sparse global seismic networks.

Global heat flows from the models are consistent with the geochemical model by [4] and close to the values determined by [5]. Local circumstances such as anomalous crustal properties in impact basins due to the deposition of cold crust at the surface result in heat flows that lie a few mW/m^2 below the global average and are considered a lower bound.

Furthermore, electrical conductivity can be obtained from the model and be compared with conductivities inferred from magnetometer data.

Acknowledgements

TR was supported by DFG grant Ru 1839/1-1, with additional funding from DFG grant Ru 1839/2-1 and the DFG program TRR 170. The models were run on the ForHLR II cluster at the Steinbuch Centre for Computing, Karlsruhe.

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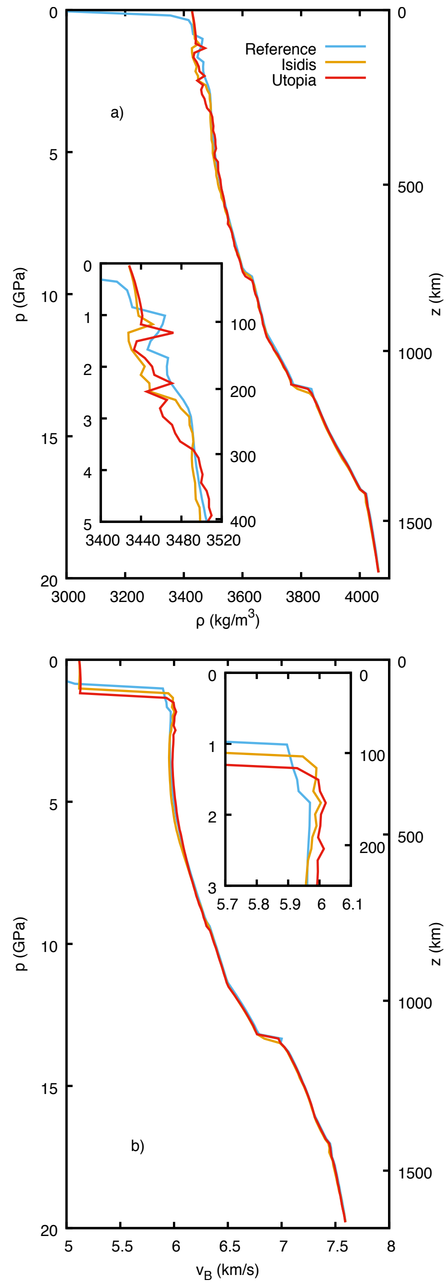

Figure 2: Present-day density and bulk sound velocity at the impact site.