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Using large impacts to constrain the thermal evolution of the terrestrial planets

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Abstract

The surfaces of Mercury, the Moon, and Mars are largely the results of interior processes that operated over the age of the solar system. These surfaces are also the location of copious amount of data (e.g., imaging, spectrometry). However, the only direct constraints available when investigating the interior evolution of terrestrial planets are related to the nature (volcanic/primordial), volume, and age of the crust. In this work we compute thermal evolution models for Mercury, the Moon, and Mars constrained by the properties of their crusts. We evaluate the geodynamical effects of large impacts in the interior evolution of each body. We focus on reproducing the inferred volume and time of emplacement of the volcanic infillings associated with large impact basins. This approach combines local datasets with global thermal histories of the terrestrial planets. We validate this method on Mercury by showing that we can reproduce the physical and spectral properties of its large basins. We apply the same methodology to Mars and the Moon.

1. Introduction

The crusts of Mercury and Mars are mostly volcanic, the result of partial melting associated with mantle convection [1,2]. The primordial lunar crust is only partially covered by volcanic material in the relatively large mare provinces, located mostly in the nearside hemisphere and in association with large impact basins [3]. Thermal or thermo-chemical evolution models are broadly consistent with the observed properties of the crusts of Mercury, Mars, and the Moon [e.g., 4—6].

The possible causal link between large impacts and subsequent impact-induced volcanism has been explored both for the Moon [e.g., 7] and for Mercury [8]. However, none of the previous works explicitly took advantage of the local datasets related to large impact basins.

2. Methods

We use the code GAIA [9] to compute thermal evolution histories for Mercury, Mars, and the Moon. We compute crustal production resulting from partial melting in the mantle. We take into account extraction of the incompatible heat sources and the modification of the solidus as a result of partial melting in the mantle. We vary the mantle reference viscosity, the amount of radiogenic material in the mantle, and the thickness of a low-conductivity regolith layer. The effect of large impacts is computed with scaling laws [e.g., 8]. We focus on the volume, depth of the source region, and temporal extent of melting associated both with mantle convection and with the effects of large impacts.

3. Constraints on the evolution

The volume of the volcanic crusts of Mercury and Mars [10,11] and the volume of basaltic volcanism on the Moon [e.g., 5] provide an estimate of the cumulative amount of partial melting produced in the mantles of these bodies. The timing of the major volcanic eruptions [2,12] provides an indication of the evolution of the thermal state of the mantle. The end of major volcanic eruptions would indicate the ending of major production of partial melt in the mantle. Large impact basins are often observed to contain volcanic material in their interiors [e.g., 13]. Stratigraphic analyses and crater counting can provide estimates for the volume and time of emplacement of this volcanic material [e.g., 14].

4. Results

Figure 1 shows crustal production from partial melting associated with mantle convection as a function of time obtained for representative thermal evolution models of Mercury and Mars. The curves are compatible both with the inferred volume of the crusts of these bodies [10,11] and with the timing of volcanic activity recorded on their surfaces [2,12].

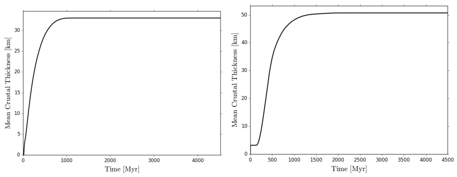

Figure 1: Crustal thickness evolution for Mercury (left) and Mars (right) from 2D cylindrical simulations of mantle convection. The thicknesses at 4.5 Gyr are compatible with the values inferred from the analysis of gravity and topography data [10,11].

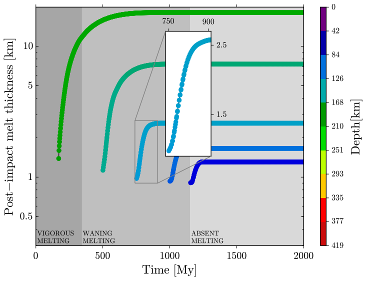

Figure 2: Melt production following an impact forming a Caloris-sized basin on Mercury at different epochs. Thickness values refer to melt produced below the final basin. Colors indicate the source depth of the melt. The grey background indicates the amount of melting associated with mantle convection (from Figure 1).

Given the large number of parameters that are required in thermal evolution models, these two constraints are relatively easy to satisfy. For an impact forming a Caloris-size basin on Mercury at different epochs in the evolution of the planet, Figure 2 shows the predicted amount of in-basin volcanism and depth of the source region. The event highlighted in the box corresponds to the time of the Caloris forming impact event on Mercury. The predicted volume and time of emplacement match the corresponding values inferred from stratigraphy and crater counting in the Caloris basin [13, 14]. These quantities depend on the values of the parameters of the evolution model, thus illustrating the possibility of including local constraints in a global evolution code approach. Further comparisons with physical and spectral properties of large basins on Mercury validate the method [15].

5. Conclusions

We present a novel method that takes advantage of both global and local constraints in computing thermal evolution models for Mercury, Mars, and the Moon. We test the method on Mercury, showing that it can properly reproduce the observed physical and spectral properties of the large basins observed on the surface. Results regarding the application of the method to Mars and the Moon will be presented.

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