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The Thermal State and Interior Structure of Mars as Predicted from 3D Thermal Evolution Models

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Abstract

Models of the interior evolution combined with geological, petrological and geophysical observations can be used to constrain the thermal history and the present-day state of the interior of Mars. We use the largest-to-date set of 3D numerical models to identify thermal evolution parameters that reproduce observational constraints. Our results show that only a limited number of models are compatible with the available constraints, and suggest an average crustal thickness of about 62 km strongly enriched in heat producing elements and a core radius of about 1850 km. A dry mantle rheology at least today along with a large increase of viscosity with pressure of about 2–3 orders of magnitude are required. The latter leads to the formation of prominent mantle plumes that are located beneath Tharsis and Elysium volcanic provinces and produce partial melt underneath Tharsis until present-day. The upcoming seismic and heat flow data of the InSight mission will provide additional constraints that will help to further reduce the range of admissible models.

1. Introduction

In this study we attempt to reconstruct the thermal history of Mars by combining large-scale numerical simulations of interior evolution with spacecraft observations and laboratory investigations of martian meteorites.

Geologic dating of surface units on Mars suggests that the planet has been volcanically active until the recent past. The concentration of volcanic activity in Tharsis and Elysium provinces suggests the location of mantle plumes beneath such regions over geological timescales e.g., [1].

Petrological analysis of shergottites suggests temperatures above 1700 K in the martian mantle during the past 500 Myr of evolution. Such high temperatures require the presence of hot mantle thermal anomalies at recent times during the planet's history [2].

Elastic lithosphere thickness data available at various times during the evolution of Mars are commonly used to estimate lithospheric temperatures. Elastic thickness values have been derived from gravity and topography admittance modelling, lithospheric flexure studies, or the brittle to ductile transition depth. Values smaller than 25 km during the Noachian epoch suggest a vigorously convecting interior and/or a warm lithosphere at that time (e.g., [3]). During Hesperian and Amazonian the elastic lithosphere thickness increased. However, values during these epochs are often associated with large timing uncertainties due to the build up of volcanic centers. Present-day elastic thickness estimates available for the north and south pole of Mars suggest values higher than 110 km [4]. In particular, the absent deflection beneath the north polar cap suggests a thick and cold lithosphere, with and elastic thickness in excess of 300 km [5].

The tidal parameters k_2 and Q are directly related to the interior structure of Mars and dissipation inside its mantle, respectively [7]. Over the past decades, with the increasing amount of tracking data, both k_2 and Q values have been revised, and the most recent estimates are 0.1697 ± 0.0027 and 99.5 ± 4.9, respectively [7, 6]. While k_2 is sensitive to the size of the liquid core, Q is directly related to the mantle viscosity, which in turn depends on the temperature, pressure and grain size [8].

2. Model

We run the largest-to-date set of 3D thermal evolution models and require best-fit models to satisfy the above-mentioned constraints. All our simulations use crustal thickness models derived from gravity and topography data. The crust is assumed to have a lower thermal conductivity and to be enriched in heat sources with respect to the primitive mantle. Our models use adiabatic heating and cooling of the mantle, include two exothermic phase changes for a core radius > 1500 km and an additional endothermic one if the core radius is 1500 km, and account for radioactive decay and core cooling. We vary input parameters such as core size, crustal thickness, conductivity and its radiogenic content, mantle viscosity and thermal expansivity. For a detailed model description we refer the reader to [9].

3. Results

Our models require a crust with an average thickness of 62 km and a core radius of 1850 km to be compatible with observations. A thinner crust is compatible with observational constraints only if the heat production rate in the Martian crust is higher than the value inferred by the gamma-ray measurements, or the model has a subchondritic mantle heat production rate (about 20% less heat producing elements than suggested by the WD94 compositional model [10]). Conversely, a thicker crust becomes marginally compatible with the observations if the crustal heat production rate is smaller than the value derived from gamma-ray observations and the present-day elastic thickness constraint for south pole of Mars is relaxed to ≥ 100 km. While core radii slightly smaller or larger than 1850 km may be compatible with the observations, we note that no model employing a core radius ≤ 1800 km can match the most recent k_2 estimate.

All our best-fit models require a dry present-day mantle rheology to be compatible with the large elastic thickness inferred for the north pole of Mars. To match the low elastic thicknesses during the Noachian epoch, models require a wet crustal rheology, but the mantle may be dry, in agreement with previous studies [11, 12]. A large viscosity increase with pressure leads to the formation of prominent mantle plumes and downwellings that can reconcile a thick present-day elastic lithosphere at the north pole of Mars with recent volcanic activity in Tharsis and Elysium.

4. Summary and Conclusions

We have used a large number of 3D numerical simulations of thermal evolution together with observational data sets to identify key parameters of the interior of Mars. Future estimates of the crustal thickness, core size and surface heat flow of the InSight mission will provide the most direct constraints for our models and

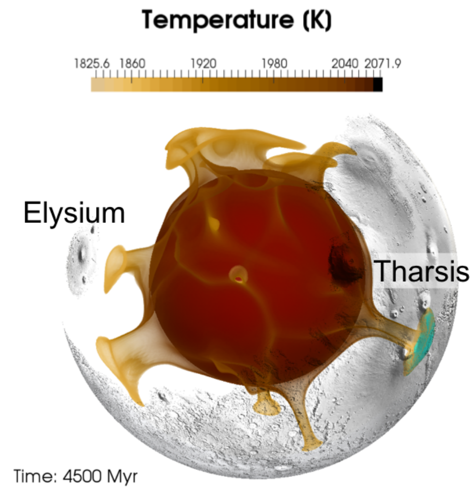

Figure 1: Temperature distribution for a best-fit model, showing mantle plumes underneath Tharsis and Elysium. The mantle plume beneath Tharsis produces melt until present day (cyan surface). The surface map is based on a MOLA shaded relief map.

will help reduce the uncertainties related to the interior structure and thermal state of the martian interior.

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