EPSC Abstracts
Vol. 11, EPSC2017-974, 2017
European Planetary Science Congress 2017

Present-day heat flow and seismicity of Mars as predicted from convective thermal evolution models

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Abstract

The InSight (Interior exploration using Seismic Investigations, Geodesy and Heat Transport) Discovery-class mission, to be launched in 2018, will perform a comprehensive geophysical investigation of Mars using a seismometer and a heat flow probe as well as precision tracking. The seismic and heat flow data are ultimately important to constrain the present-day interior structure and heat budget of the planet, and, in turn, offer constraints on its thermal and chemical evolution [1]. As the InSight lander will perform its measurements at a single location, in the Elysium Planitia region [2], numerical simulations of the dynamics of the interior can greatly help to interpret the data in a global context. In this study we present 3D numerical thermal evolution models of Mars and focus on the present-day state. Furthermore, we compare our results with available estimates of elastic lithosphere thickness and seismicity.

1. Introduction

At present, the Moon is the only body beside the Earth for which globally significant heat flow and seismic measurements are available. For Mars, indirect estimates from lithospheric loading models are used to infer the surface heat flow. However, the only available estimate of the present-day lithosphere thickness suggests a value larger than 300 km at the north pole [3]. This value corresponds to a heat flow smaller than 15 mW/m^2, which, if globally representative, is significantly lower than that predicted by numerical simulations [4, 5] employing the well accepted compositional model of [6]. This discrepancy led to speculations that the concentration of heat producing elements in the interior of Mars may be subchondritic or that the secular cooling of the planet could be smaller than predicted. Instead, we show that mantle plumes can introduce significant variations in the average surface heat flow [7]. Assessing the extent of surface heat flow variations is particularly important since one of the main goals of the InSight mission is to constrain the average surface heat flow from one single measurement. Together with the Urey ratio (i.e., the heat production rate divided by the rate of heat loss) as obtained from numerical models, the average surface heat flow can be used to constrain the heat production rate in the Martian interior [8].

Previous seismic measurements on Mars have been performed in the mid 1970's by the Viking seismic experiment. However, the instrument's poor coupling to the ground led to a high noise level produced by the wind-induced lander movements, making it difficult to identify events of seismic origin [9]. Yet estimates of present-day seismicity based on the analysis of surface faults predict values between those obtained for the Earth and the Moon [10, 11], even though it remains rather uncertain which of the faults are currently active on Mars. In this study, we use thermal evolution models to derive the amount and distribution of Mars' seismicity.

2. Model

We employ the mantle convection code GAIA [12] to compute the thermal evolution of Mars in a 3-D spherical geometry. Our models assume a fixed crust with a variable thickness as inferred from gravity and topography data, which is enriched in radiogenic heat sources according to the surface abundances inferred from gamma-ray measurements. We vary the mantle reference viscosity as well as the depth-dependence of the viscosity, consider constant and variable thermal expansivity, vary the crustal thermal conductivity, and the size of the core.

3. Results

The surface heat flow pattern is dominated by the crustal structure. However, upon considering a viscosity increase with depth of about two orders of magnitude, the signature of mantle plumes becomes visible on the surface heat flow map (Fig. 1). Such heat flow anomalies introduced by mantle plumes remain confined to narrow regions and are unlikely to affect the InSight measurement. Moreover, north and south pole elastic lithosphere thicknesses based on the thermal structures obtained from our models are consistent with the available present-day estimates.

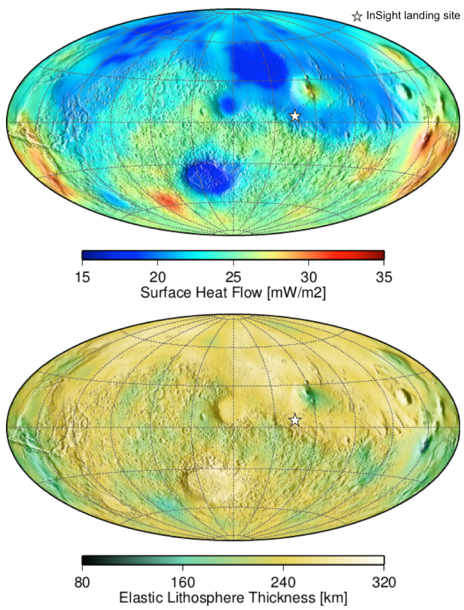

Figure 1: Distribution of the surface heat flow (top) and elastic lithosphere thickness (bottom) after 4.5 Gyr of thermal evolution (case 3 from [7]).

Furthermore, we derive the amount and distribution of present-day seismicity from the 3D thermal evolution models. We find similar but spatially anticorrelated seismic moments produced by convective stresses and stresses caused by cooling and planetary contraction, and consequently a relatively homogeneous distribution of the sum of seismic moments. Our results predict an annual moment release between 10^{16} Nm and 10^{19} Nm, similar to the values presented previously in [10] and [11]. However, while [11] used a mapping of tectonic surface faults to predict the spatial distribution of epicenters, we derive the distribution from the thermal evolution (Fig. 2). Besides the Null-Hypothesis of a uniform distribution and the model of [11], this provides a new, self-consistent, competing hypothesis for both the amount and distribution of seismicity on Mars.

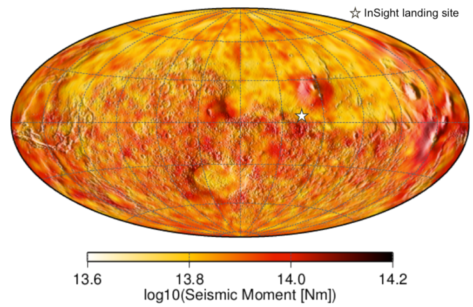

Figure 2: Distribution of the cumulative seismic moment obtained by adding the contributions from convective stresses and stresses produced by planetary contraction. The map shows the median of more than 10 models averaged on a $3\times3^\circ$ grid to filter out small scale structures that may be model dependent.

4. Conclusions

The 3D thermal evolution models we present allow estimating the global heat flow from a single-point measurement with InSight. The presence of plumes resolves the polar lithosphere thickness paradox. Additionally a new, self-consistent seismicity distribution model can be derived.

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