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Effect of width, amplitude and position of a CMB hot spot on core convection and dynamo action

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Abstract

Within the fluid iron cores of terrestrial planets, convection and hence the generation of global magnetic fields are controlled by the overlying rocky mantle. The thermal structure of the lower mantle determines how much heat is allowed to escape the core. Hot lower mantle features, like the thermal footprint of a giant impact or hot mantle plumes will reduce locally the heat flux through the core mantle boundary (CMB) and thereby weaken core convection and affect the magnetic field generation process. In this study, we numerically investigate how parametrised hot spots at the CMB with arbitrary size, amplitude and position affect core convection and hence the dynamo. The effect of the heat flux anomaly is quantified by changes in global flow symmetry properties, such as the emergence of equatorial antisymmetric and axisymmetric (EAA) zonal flows. For pure hydrodynamic models the EAA symmetry scales almost linearly with its respective amplitude and size, whereas self-consistent dynamo simulations typically either suppress or drastically enhance EAA depending mainly on the length scale of the heat flux anomaly. Our results suggest, that the horizontal extent of the anomaly should be on the order of the outer core radius to significantly affect flow and field symmetries. As an implication to Mars, the study concludes that an ancient core field modified by a CMB heat flux anomaly is not able to heterogeneously magnetise the crust to the present-day level of north-south asymmetry.

1. Introduction

The three terrestrial planets, Earth, Mercury and Mars harbour or once harboured a dynamo process in the liquid part of the iron-rich core. Vigorous core convection shaped by rapid planetary rotation is responsible for the generation of global magnetic fields. In terrestrial planets the amount of heat escaping the core is set by the thermal structure of the overlying mantle convection. As the vigorous core convection assures efficient mixing and hence a virtually homogeneous temperature at the core side of the CMB T_{core}, the flux through the CMB is entirely controlled by the lower mantle temperature T_{lm}, hence

$$q_{cmb} = k\frac{T_{lm} - T_{core}}{\delta_{cmb}}\ , \tag{1}$$

where δ_{cmb} is the vertical thickness of the thermal boundary layer on the mantle side and k the thermal conductivity. Hot mantle features like convective upwellings, thermal 'footprints' of giant impacts or chemical heterogeneities locally reduce the heat flux rate through the CMB. E.g. for the planet Mars, low degree mantle convection or giant impacts might have significantly affected the core convection and the morphology of the induced magnetic field. The strong (south-)hemispherical preference of the crustal magnetisation can for example be explained by an ancient dynamo which operated more efficiently in the southern hemisphere [1]. Indeed, turned out that dynamo models obeying magnetic fields, which show a geometrically corresponding intensity distribution (hemispherical fields) are typically oscillatory and hence can not explain the thick and unidirectional magnetisation on Mars [2].

However these numerical models relied on a rather simplistic of the variation of the CMB heat flux as a single, large scale spherical harmonic (Y_{10}) was used. We therefore test the robustness of pessimistic models of the ancient Martian core with using a complex heat flux anomaly of variable width, amplitude and position.

2. Results

The main effect of the large-scale thermal anomaly is to introduce a global asymmetry on the mean temperature by reducing the heat flux in the northern and increasing it in the south. Mean flows seeking the equilibrate this temperature asymmetry are diverted into azimuthal directions by the dominating thermal wind:

$$\frac{\partial \overline{u_\phi}}{\partial z} = \frac{RaE}{2Pr} \frac{1}{r_{cmb}} \frac{\partial \overline{T}}{\partial \theta} , \qquad (2)$$

where the colder (southern) hemisphere obeys much stronger convection and hence magnetic field induction (see figure 1).

Our results suggest that the fundamental temperature asymmetry developes independent of the anomaly width and position, a surprising result. Further we can show, that in hydrodynamic simulations without a magnetic field the relative strength of EAA-symmetric flows scales almost linearly with its respective amplitude and width, whereas in dynamo simulations the magnetic field either suppresses antisymmetric flows when weaker amomalies are applied or drastically enhances them for the stronger anomalies. We clearly identify and quantify the action of the magnetic field on the asymmetry of flow and temperature. Further we show that also smaller and weaker anomalies do not yield a hemispherical magnetic field what is both, stable in time and hemispherical enough.

3. Summary and Conclusions

Our numerical investigation of a planetary dynamo model subject to heterogeneous CMB heat flux, indicates three main conclusions. It turned out, that the fundamental temperature asymmetry driving equatorial antisymmetric and axisymmetric flows (EAA) emerges independent of the width, amplitude and position of the CMB hot spot. However, including the action of the induced magnetic field, we state that the horizontal extent of a CMB heat flux anomaly needs to exceed the radius of the core to affect core convection and magnetic field induction significantly. Finally as an implication to Mars, we conclude the hemispherical distribution of the present-day crust can not exclusively explained by an ancient core dynamo inducing a hemispherical magnetic field [3].

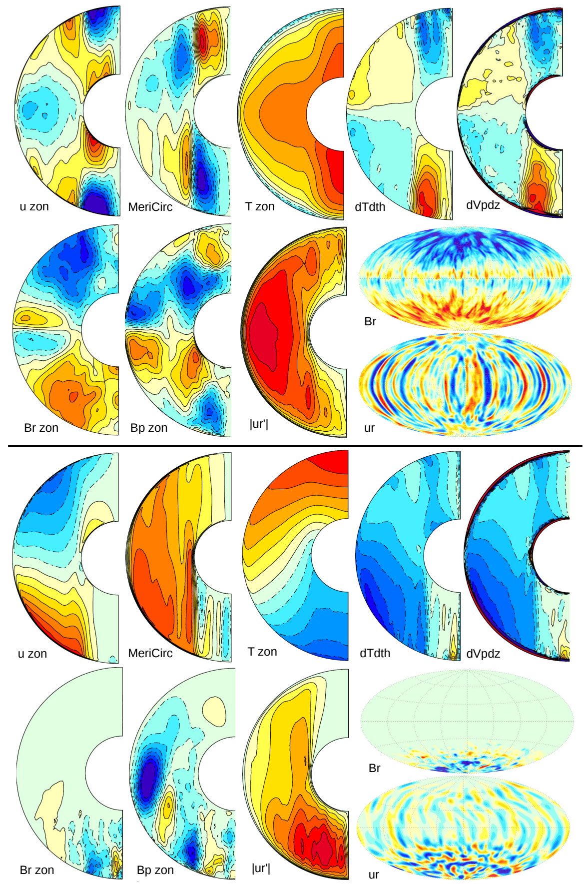

Figure 1: Mean flow and field properties for a case of homogeneous outer boundary heat flux (top part) and when a Y_{10}- heat flux anomaly is added (lower part).

References

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