Self-Sustaining Dynamos in Massive Terrestrial Exoplanets?

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Introduction

In the last years the number of known exoplanets has increased dramatically [1, 2], and more and more massive terrestrial exoplanets, or Super-Earths, are found. Naturally, the question arises whether these planets provide habitable conditions for life, which is on one hand constrained by the position of the planet in its stellar system, the spectral type of the parent star and the atmospheric composition of the planet. If the planet is located in the so-called habitable zone (HZ, [3]), liquid water can exist and Earth-like life is conceivable. If other solvents than water are allowed for, the HZ can be extended to a "life supporting zone" [4, 5], which is a more general description of a zone around a star, where different solvents can exist in the liquid phase and exotic life is conceivable. On the other hand, the planet has to be shielded from high-energetic particles in order to allow life to emerge and evolve, thus a planetary magnetic field is crucial for habitability. So far no magnetic fields around planets outside the solar system could be observed, since the sensitivity needed for this task has only been achieved recently. The LOFAR array would provide the ability to detect radio emissions from the interaction of planetary magnetic fields with the parent star [6], though this would probably only work for extrasolar giant planets (EGPs, 0.3 M_J to 15 M_J, Burrows et al. [7]). Nevertheless, the number of EGPs has increased since Stevens proposed this possibility, and by now our investigation reveals 32 planets as candidates for such observations, considering that for many stars no data are available in the NEXXUS database [8]. But what influence does the size of a planet have on its ability to generate a self-sustaining magnetic field? Do conditions in massive terrestrial exoplanets favor or hamper magnetic field generation?

A Simple Model

The first step in answering this question is the development of an interior structure model, which has been carried out by a number of authors (e.g. [9, 10]), using different equations of state (EoS) and parameterizations for pressure- and temperature-dependent viscosity. The choice of an adequate EoS is essential, since the influence of increasing pressure on conditions in the lowermost mantle has to be kept in mind in order to determine the ability of a planet to generate a self-sustaining magnetic field. Although the behaviour of mantle and core materials at very high pressures is still very uncertain, several attempts have been made to find suitable descriptions of important quantities at these conditions (e.g., [11]). It is vital to choose the EoS that fits these conditions best [12, 11], by combining experimental data at low pressures with theoretical calculations and extrapolations to high pressures prevalent in massive terrestrial planets. Using results from interior structure models and employing a parameterized convection model for the mantle (e.g., [13]), the cooling behavior of a planet can be evaluated, which ultimately governs the dominant mechanism of heat transport, conduction or convection, and therefore the potential to sustain a magnetic field over geological time scales.

Results

Wagner et al. [10] have used three different equations of state (EoS) to calculate gradients of density, pressure, gravitational acceleration and temperature within planets of 1 $M_\oplus$, 5 $M_\oplus$, and 10 $_\oplus$ planets, respectively, employing a temperature- and pressure-dependent viscosity. The Keane-EoS seems to be the most appropriate EoS in the case of Super-Earths [11], and using the results from Wagner et al. [10] for this case by estimating the appropriate values from the model curves, the heat flow across the core-mantle boundary, Q_C, can be calculated, following Nimmo [13], where $Q_C \propto r_c^2$, and r_c is the radius of the core-mantle boundary. For the case of 5 $M_\oplus$ and 10 $M_\oplus$ planets heat flows of $Q_{C,5\ M_\oplus} = 5.61 \cdot 10^{12}\ W$ and $Q_{C,10\ M_\oplus} = 12.13 \cdot 10^{12}\ W$, respectively, have been determined, which are rather low in contrast to a mean value for the Earth of $Q_{C,\oplus} \sim 9\ TW$, but seem reasonable given the high viscosity of $\eta \sim 10^{23} Pa\ s$ in the mantles of these massive planets. In contrast, the heat conducted down the adiabat $Q_k \propto r_c^3$ is calculated to be $Q_{k,5\ M_\oplus} = 33.38 \cdot 10^{12}\ W$, and $Q_{k,10\ M_\oplus} = 93.60 \cdot 10^{12}\ W$. These values are much higher than the respective heat flows across the core-mantle boundary, which means that heat in the core of these planets is primarily transported via conduction. It has to be noted, though, that the parameterized approach is problematic [14] and could lead to a misestimation of the CMB heat flow. Moreover, a couple of quantities, like the thermal expansivity or specific heat capacity, are still poorly constrained at very high pressures, which contributes to the uncertainty of this approach. Finally, the estimation of values from the model curves of Wagner et al. [10] naturally leads to inaccuracies, though the errors introduced thereby are certainly insignificant in contrast to the former two shortcomings of this model.

Conclusions

The simple model described above reveals a dominant role of heat conduction in the cores of massive terrestrial planets. This means that a key criterion for the existence of self-sustaining dynamos is not met, i.e. vigorous convection. This is in agreement with the results from Stamenković et al. [11], who calculated a series of quantities, like viscosity, thermal expansivity, thermal conductivity, and specific heat capacity, for the mantles of Super-Earths, and came to the conclusion, that conduction will be the dominant heat transport mechanism in the mantles of these planets, differentiation might be questionable, and thus magnetic fields will be very unlikely. In the model of Gaidos et al. [15] magnetic fields in massive terrestrial planets could be achieved, albeit they were less probable and less long-lasting with increasing planetary mass. The influence of radiogenic heat in the core is neglected in all models, and, based on Earth-like abundances of ^{40}K, ^{232}Th, ^{235}U, and ^{238}U, a next step should be to consider a possible influence of this energy source on the viscosity in the core and mantle, and thus on the ability to generate a magnetic field. Moreover, the influence of high pressures and subsequent high viscosities on compositional convection should be investigated.

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