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Induction heating of planetary interiors

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Abstract

We present a calculation of the energy release in planetary interiors caused by induction heating. If an exoplanet orbits a host star with a strong magnetic field, it will be embedded in periodically varying magnetic environment. In our work, we consider only a dipole field of the host star and assume the dipole axis to be inclined with respect to the stellar rotational axis, which causes the magnetic field to vary. In this case, the varying magnetic field surrounding the planet will generate induction currents inside the planetary mantle, which will dissipate in the planetary interiors. We show that this energy release can be very substantial and in some cases even lead to complete melting of the planetary mantle over geological timescales, accompanied by the enhanced magnetic activity.

1. Introduction

Unlike the Sun, low-mass M dwarfs often are observed to have strong magnetic fields of a few hundred Gauss or more. We consider TRAPPIST-1 system as an example and calculate the induction heating of planetary mantles of the seven TRAPPIST-1 planets. In the Solar system, the environmental conditions differ substantionally from the TRAPPIST-1 system, with the only exception of the Galilean moons. The Galilean satellites are embedded in the magnetic field of Jupiter, varying due to Jupiter's rotation and the dipole axis inclination of $\approx 10^\circ$. Although the magnetic field of Jupiter is not strong enough to heat the interiors of the Galilean satellites, it leads to generation of induced dipole fields inside the moons. Observation of these induced fields allowed to discover salty water oceans under the surfaces of Europa and Callisto [1, 2].

2. Method

First, we calculate the magnetic field inside the planetary mantle embedded into varying external magnetic field. We apply the formulas for the magnetic field components for a sphere with non-homogeneous conductivity presented by [3]. We divide the planetary mantle into layers assuming the conductivity to be constant inside a layer and solve the induction equations for the magnetic and electic fields and for the current inside every layer and in the central part of the sphere. Knowing the current in every layer, one can easily calculate the energy release in it. Then, we use the code CHIC [4] to model the corresponding magmatic effects in the planetary mantle. We calculate the amount of melt in the mantle, and the amount of the induction heating-triggered volcanic outgassing.

3. Results

Fig. 1 presents an example of our calculation for the planet TRAPPIST-1c, which has a radius close to the one of the Earth. Since the masses of the TRAPPIST-1 planets have not been measured yet with a high precision, we assume an Earth-like composition in our calculations. We also assume an Earth-like conductivity profile (shown in Fig. 2). Fig. 1 shows energy release rate inside the planet depending on the depth. Total energy release inside the planet equals approximately 10^{22} erg/s. We assume the dipole field strength of TRAPPIST-1 equal to 600 G. As one can see, energy release peaks at about 0.9 planetary radii. Below approximately 0.8 planetary radii magnetic field already substantionally declines, leading to insignificant energy release. On the other hand, in the upper part of the mantle above 0.9 planetary radii energy release is weak due to low conductivity (see Fig. 2).

We modelled corresponding magmatic effects in

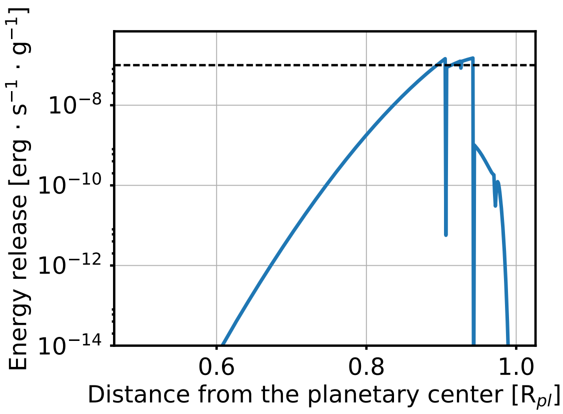

Figure 1: Energy release rate in the mantle of the exoplanet TRAPPIST-1c. The dashed line indicates approximate level of the local heat necessary to melt the mantle and create a magma ocean.

planetary interiors using the code CHIC. Our results show, that in case of TRAPPIST-1c a magma ocean is formed beneath the planetary surface, similar to the one of Io. Therefore, similar to Io, one can expect volcanic activity at this planet to be strong.

4. Summary and Conclusions

We have shown that induction heating is substantial in the interiors of planets orbiting strongly magnetized M dwarfs. Sometimes the heating is strong enough to melt the planetary mantle and produce an Io-like magma ocean under the planetary surface. In case of weaker heating, it still leads to enhanced volcanic activity and increased outgassing of greenhouse gases. Our results indicate that induction heating should be taked into consideration among other effects when studying the evolution of exoplanets orbiting M dwarfs, especially for close-in planets, but also for some planets in the habitable zones of M dwarfs. Our results are summarised in [5].

Acknowledgements

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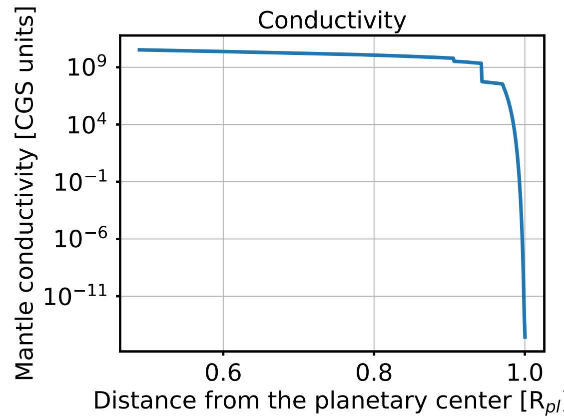

Figure 2: Elecrical conductivity profile of the planetary mantle for TRAPPIST-1c, assumed for calculations.

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