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The effect of an electrically conducting lower mantle on planetary dynamos in large terrestrial exoplanets

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Abstract

In the past decade there has been an explosion in the number of exoplanets that have been discovered. These newly discovered planets have proven to be extraordinarily diverse in their physical characteristics. This has allowed planetary scientists to explore examples of planets beyond the small sample size of our solar system. Of particular interest to interior modellers is the class of planets known as "super-Earths", defined as solid exoplanets with a mass greater than one Earth mass, without a significant gas envelope [1]. Inside these planets exist temperatures and pressures which are far greater than those found within the solid planets of our solar system. With these extreme conditions comes the possibility of exotic material properties, which could affect the internal dynamics and evolution of the planet.

Recent theoretical work has predicted the dissociation of $MgSiO_3$ at the conditions of the core mantle boundaries of larger super-Earths ($\geq 8M_e$, where M_e is the mass of the Earth) [2],[3]. These dissociated silicates should conduct electricity with a conductivity comparable to that of liquid iron [4]. Since $MgSiO_3$ is likely a major constituent of the mantles of any terrestrial exoplanet, we should expect the lower mantles of large super-Earths to be electrically conductive.

A conductive lower mantle should have an effect on any dynamo generated magnetic field in two ways. First, since magnetic fields freeze into conductive materials, an electrically conducting lower mantle can impart a Lorentz force to the fluid part of the core. This will affect the internal dynamics of the dynamo by changing the force balance. Secondly, any time varying components of the planetary magnetic field will be severely attenuated by the conducting mantle. This is because of a screening effect that conductors have on time varying electrical or magnetic fields. In this paper we use a numerical dynamo model with a surrounding conducting shell to consider both of these effects.

1. Methods

We consider a terrestrial planet of approximately 9M$_e$, from [5] we estimate that this leads to the simplified planetary structure shown in figure 1. The exact details

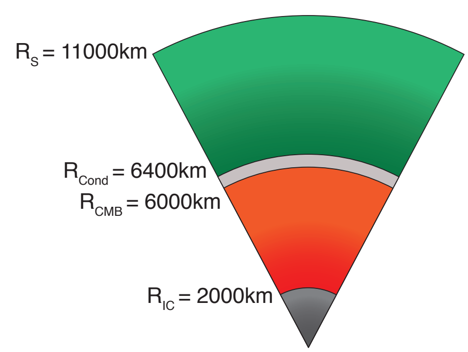

Figure 1: A slice of the simplified planet we consider in this study. In this figure, green represents the non-conducting mantle and crust, silver represents the electrically conducting lower mantle, red represents the liquid outer core, and dark grey represents the solid inner core. The approximate radii of the transitions between regions are shown. For this model, a conducting shell thickness of 400km is used.

of our simplified planetary model are somewhat arbitrary, as the depth at which the dissociation of $MgSiO_3$ happens is dependant on pressure [2],[3]. A conducting layer of arbitrary thickness can be made simply by adjusting the mass of the planet, or the size of the core.

In our study we assume that a liquid core is present, and that the buoyancy flux out of the core is sufficient to drive a dynamo. In order for a liquid core to be present, the core mantle boundary temperatures are required to be much hotter than typically assumed [5]. This could easily be the case early in the planets history, or if different conditions than those assumed by [5] are present. The other assumption we make is that sufficient buoyancy flux is present to drive a dynamo. Recently [6] showed that the presence of a layer of dissociated mantle material in the lower mantle would drastically increase the heat flux out of the core, especially during the early history of the planet. This extra heat flux, combined with compositional sources, should be enough to drive a planetary dynamo.

We use the Kuang-Bloxham numerical dynamo model, which solves the 3D, Boussinesq, MHD equations in a rapidly rotating spherical shell [7]. We include a solid conducting layer above the dynamo region with various values for its electrical conductivity and thickness.

2. Results

The addition of even a thin electrically conducting layer surrounding the dynamo region has a drastic effect on the observed magnetic field. In a conducting solid, the magnetic field obeys a diffusion equation. Given a time varying magnetic field at the CMB (supplied by the dynamo), it can be shown that the observed field at the top of the conducting region is attenuated as

$$e^{-r/\sqrt{2\eta\tau}} \tag{1}$$

if the spherical geometry is approximated as an unbounded plane (this is reasonable if the conducting mantle layer is thin). Here, r is the radial distance from the CMB, τ is a characteristic timescale, and $\eta = 1/\sqrt{\mu_o\sigma}$, is the magnetic diffusivity where μ_o and σ are the magnetic permeability and the electrical conductivity of the material respectively [8].

As other studies have pointed out [9], in planetary dynamos the timescale τ scales approximately inversely to the spherical harmonic degree L and the magnetic Reynolds number ($Rm = U\lambda/\eta$) where λ and U are length and velocity scales. This means that small scale structures (large L) should vary faster in time than smaller scale structures, and be preferentially damped at the surface because of the screening effect of the conducting layer.

In our models we indeed find that this screening effect acts to reduce the observed timescale of the magnetic field. Secular variation, as measured by the standard deviation of the radial magnetic field at the surface is reduced by a factor of three in our models which include a thin conducting layer, when compared to models which lack this layer.

We also find that the magnetic field characteristics depend on the conductivity and thickness of the layer. This has implications for the observed magnetic field outside of the planet.

3. Summary and Conclusions

We have added a conducting layer to the lower mantle of a planet, to simulate the effect of the dissociation of $MgSiO_3$ in the lower mantles of large super-Earths. We find that this significantly affects the observed surface field by reducing the secular variation observed at the surface.

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