EPSC Abstracts
Vol. 5, EPSC2010-910, 2010
European Planetary Science Congress 2010

No Magnetic Fields on Super-Earths?

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Abstract

We investigate the ability of Super-Earths to generate thermally and compositionally driven magnetic dynamos. For this we model the thermal evolution and convection of planets with an Earth-like composition and structure of sizes ranging from 1 to 10 Earth masses (M_{Earth}) with a parameterized 1D boundary layer model. We especially include the pressure dependence of viscosity into our models, with the scope to understand how the pressure-viscosity coupling of the viscosity changes the convection in the mantles of Super-Earths and thus the magnetic field generation. We observe that the pressure dependence of viscosity becomes an important factor for the mantle convection of Super-Earths - resulting in a highly sluggish convection regime in the lower mantle for those planets. Depending on activation volume, we observe with growing planetary mass the formation of a conductive lid over the core mantle boundary (CMB), termed low-lid, where convection velocities cease and where heat transport is only due to conduction. The low-lid acts as a thermal insulator, leading to lower core cooling rates in comparison to non-pressure dependent-viscosity models. Even for Super-Earths with initial temperatures close to mantle melt the insulation effect of the low-lid is strong enough to reduce the heat flux below the critical heat flux necessary to form a thermally driven magnetic dynamo. The compositional dynamo can occur on Super-Earths but only for shorter time scales and most likely with lower field intensities than on less massive planets. Magnetic field generation on Super-Earths cannot be excluded, but it will be much rarer than on less massive planets.

1. Model

Using boundary layer theory [2] we self-consistently model the thermal evolution and the inner core growth of Super-Earths. We expand the 1D model into a more generalized form, where we adjust all planetary characteristics to scale with the free choice of planetary mass. We assume that the investigated Super-Earths have the same composition and average surface temperature as Earth. The core mass fraction (CMF) is kept Earth-like at 32.59%. We derive scaling laws for latent heat, gravitational energy and obtain melting curves consistent with the K'-Equations of Stacey [1]. Our main scaling parameter for the core dynamics is the Grüneisen parameter, combining vibrational and electronic contributions. We especially derive the viscosity $\eta(p,T)$ and the pressure dependence of activation volume $V^*(p)$ from basic microscopic and thermodynamic principles adjusted for the large pressures found on Super-Earths (with E^*, p_{ref} and T_{ref} being the activation energy and the reference pressure and reference temperature).

$$\eta(p,T) \propto \exp\left(\frac{(E^* + pV^*(p))T_{ref} - (E^* + p_{ref}V_{ref}^{\ *})T)}{RT_{ref}T}\right) \qquad (1)$$

2. Results

A magnetic field can only be generated in a, at least partially, molten core. To find out if a planetary core is liquid we need to derive melting curves for impure iron. Most extrapolated melting curves to pressures relevant to Super-Earths use equations of state that are thermodynamically inconsistent - such as the ones using the Vinet or the Birch Murnaghan (BM) equation of state. Especially do they allow for the Grüneisen parameter to get arbitrarily close to zero. Stacey has shown that the first derivative of the bulk modulus and the Grüneisen parameter converge for $p \rightarrow \infty$ to non-zero values, and that the compression found in the Earth's core is close to this limit [1]. This allows deriving the solidus for impure iron using the Lindemann equation of state for Earth and Super-Earths. The melting curves are becoming almost linear as we approach the pressure domain relevant to Super-Earths. This makes it much more difficult for Super-Earths to have partially liquid cores – making dynamo generation more difficult. The sluggish convection and the partial low-lid formation due to the pressure dependence of viscosity lead to a highly reduced CMB heat flux.

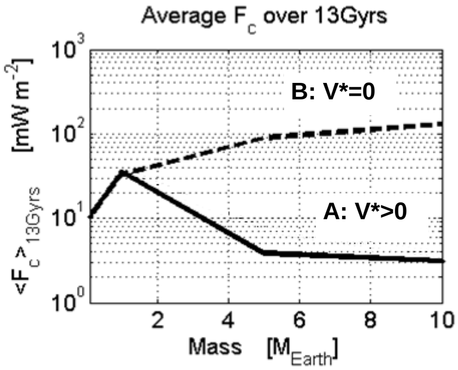

Figure 1: Average CMB heat flux for Super-Earths for realistic, pressure dependent model A and unrealistic, pressure independent model B.

Using the Wiedemann-Franz law and the Bloch-Grüneisen theory we determine the critical heat flux necessary to generate a purely thermal dynamo, which is strongly increasing for more massive planets (ρ_{cmb} is the density, T_{cmb} the temperature, g_{cmb} the gravitational acceleration, k_{cmb} the thermal conductivity and $K_{T,cmb}$ the bulk modulus, all at the planet's core side of the CMB).

$$F_{crit} \approx k_{\text{cmb}} \cdot \left(\frac{\mathrm{d}T}{\mathrm{d}r}\right)_{S} \propto \frac{\rho_{cmb}{}^{3.6} \cdot T_{cmb} \cdot g_{cmb}}{K_{T,cmb}} \tag{2}$$

We find that Super-Earths have at all times CMB heat fluxes below the critical heat flux. Therefore Super-Earths cannot generate a purely thermal dynamo.

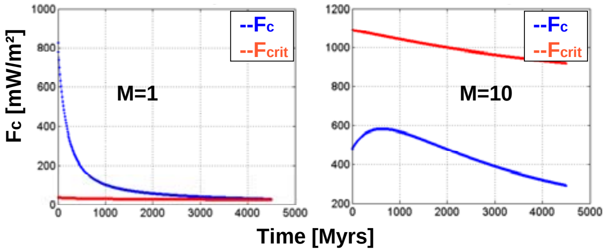

Figure 2: CMB heat flux F$_c$ in comparison to critical heat flux to drive a thermal dynamo F$_{crit}$ for 2 planets (Earth (M=1) and one Super-Earth (M=10)) for a time evolution of 4.5Gyrs.

At temperature profiles suggested by [3] and many others we observe that a pure iron core is completely frozen. An impure core would be partially liquid. However, due to the sluggish lower mantle convection, the core is heated during the entire evolution - thus enabling a compositional dynamo. Assuming that the CMB temperatures are larger than the literature suggests, which is in fact very likely as initial temperatures might scale almost linearly with planetary mass, we still find very low CMB heat fluxes and the inner core growth is very slow. We formulate an energy budget equation necessary to drive a compositional dynamo, similar to [2]. And find that the necessary energy criteria can be satisfied by Super-Earths, but only for shorter time scales compared to an Earth-sized planet, making compositional magnetic field generation able for shorter time scales on Super-Earths than on smaller Earth-like planets.

3. Summary and Conclusions

For the thermal profiles suggested by literature magnetic fields cannot be generated on Super-Earths as cores are frozen at all times or if not, they are heating up. Realizing that the literature temperature values are purely ad hoc assumptions, we look at higher initial CMB temperatures with the maximum temperature, assuming mantle melt at the CMB. This defines energetically a best-case scenario to generate a dynamo. Here we find that Super-Earths cannot generate a thermally driven dynamo due to the low heat fluxes and the large critical heat fluxes. We cannot exclude a compositional dynamo, but we find shorter life times on Super-Earths than for smaller Earth-like planets. Due to the small cooling rates we expect as well a weak magnetic field during this compositionally driven dynamo lifetime.

References

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