

Internal structure, thermal history and magnetic field generation in Super-Earths. A. Boujibar¹, P. Driscoll² and Y. Fei¹, ¹Geophysical Laboratory, Carnegie Institution for Science, 5251 Broad Branch Road, Washington, DC, 20015 (asmaa.boujibar@carnegiescience.edu), ²Department of Terrestrial Magnetism, Carnegie Institution for Science, 5241 Broad Branch Road, Washington, DC, 20015.

Introduction: The presence of strong magnetic fields is a necessary ingredient for habitability by protecting planetary surfaces from high energy charged particles and reducing atmospheric loss. Recently a large and diverse population of extrasolar planets have been discovered that include rocky planets with a range of bulk densities. While the interior of these planets remains obscure, the potential detection of exoplanetary magnetic fields would provide critical information about their interior structure, dynamics, and thermal histories.

Magnetic field generation requires the presence of an electrically conductive fluid, large scale rotation, and fluid motion that is driven, for example, by thermal or compositional convection. The strength of the magnetic field is controlled, in part, by the convective vigor in the dynamo region, which for rocky planets is modulated by the cooling rate of the overlying silicate mantle. Previous studies showed that Super-Earths (rocky exoplanets more massive than Earth) could generate magnetic fields with an intensity at the core surface up to twice the present-day geomagnetic field [1]. However, these studies relied on poorly constrained extrapolations for the phase diagrams and material properties to the high pressures and temperatures reached inside Super-Earths.

Recent first-principles calculations have suggested the dissociation of MgSiO_3 into SiO_2 and MgO oxides either at 0.68 or at 2.5 TPa for an adiabatic mantle temperature profile [2-3]. While Tsuchiya & Tsuchiya predicted a direct dissociation of post-perovskite MgSiO_3 [3], Umemoto et al. suggested the appearance of other ultra-high pressure silicate phases (MgSi_2O_5 and Mg_2SiO_4) at 0.7 TPa, before their dissociation at ~ 2.5 TPa [2]. Since oxides are expected to have significantly different physical properties than silicates, especially for their thermal conductivity, these phase transitions are likely to have important implications for the thermal evolution and hence the generation of magnetic fields in Super-Earths.

In this study, we examine density and pressure profiles for Super-Earths with a core mass fraction equivalent to Earth and a pure MgSiO_3 mantle composition. In addition, we investigate masses of Super-Earths where MgSiO_3 dissociates into SiO_2 and MgO , with core mass fractions ranging those of Mars to Mercury (~ 0.2 to ~ 0.7). We also explore the core-mantle boundary (CMB) temperatures for which the core starts

crystallizing, a process that can maintain a compositionally driven dynamo.

Methods: We modeled the internal structure of Super-Earths using unidimensional differential equations for mass, gravity, pressure, temperature and density profiles [e.g. 1]. We assumed adiabatic temperature gradients within the mantle and core. For the presented models of Super-Earth interior, we considered up to 6 layers: peridotitic upper mantle, perovskite (pv), post-perovskite (ppv), post-ppv phases being either oxides $\text{MgO}+\text{SiO}_2$ or a combination of $\text{MgSiO}_3+\text{Mg}_2\text{SiO}_5$, liquid outer core, and solid inner core. Transitions between these layers were taken from previous experimental studies for peridotite-pv [4] and pv-ppv [5], and ab-initio calculations for ppv-post-ppv [2-3]. The transition to the solid inner core happens when the core temperature profile intersects Fe liquidus [6].

Results:

Effect of planetary size: Pressure and density profiles within the interior of Super-Earths with 1 to 10 Earth masses (M_E) and 0.32 core-mass fraction (CMF) are shown in Figure 1. For these models, we considered a temperature at the core-mantle boundary (CMB) similar to the mantle solidus [6].

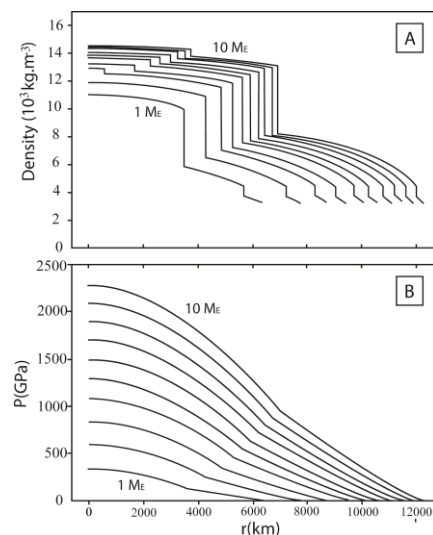


Figure 1: Density (a) and pressure (b) profiles in Super-Earths of 1 to 10 M_E with a core mass fraction (CMF) of 0.32, considering a temperature at the core mantle boundary of 4000 K.

Our results suggest that under these conditions, the presence of a solid and liquid core occurs for Super-

Earths with a mass larger than $2M_E$, due to the slower increase of the mantle solidus at the CMB than melting temperature of Fe, with increasing planetary mass (Figure 1a). The presence of the inner core is sensitive to assumed CMB temperature and extrapolation of melting curve of Fe, which both likely depend on composition. Moreover, mantles reach the pressure of the transition to post-ppv when Super-Earths are larger than $6M_E$ with little temperature dependence.

Ultra-high pressure phase transitions in the mantle: Figure 2 gives ranges of mass and core mass fraction (CMF) where the mantle reaches high enough pressures (>700 GPa) to destabilize post-perovskite $MgSiO_3$ and form post-ppv phases. Temperature at the core-mantle boundary (T_{CMB}) is considered constant for all models and at the mantle solidus [6]. Since temperature has a weak effect on these phase transitions [2], changing T_{CMB} would not affect results for this phase transition.

For a constant planetary mass, increasing CMF yields lower pressures at the bottom of the mantle. As a consequence, to reach high enough pressures to dissociate $MgSiO_3$ into oxides or post-ppv silicate polymorphs [3] Super-Earths with a relatively small Earth/Mars-like CMF (0.2-0.33) require planetary mass of 6-7 M_E compared to 14-16 M_E for a Mercury-like CMB (0.65) (Figure 2).

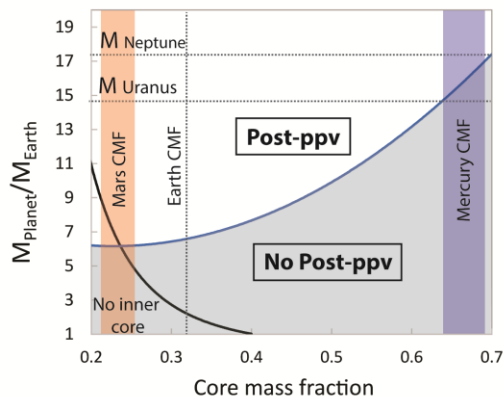


Figure 2: Fields of core mass fractions and planetary masses of Super-Earths, where post-perovskite is expected to dissociate into MgO and SiO_2 oxides or transitions into post-ppv silicate polymorphs. We considered a pressure of 700 GPa for this transition, based on first-principles calculations [2]. Black curve shows also masses where the core starts crystallizing.

Core crystallization: Solidification of an inner core can drive compositional core convection by the release of light elements and assist the generation of a magnetic field. Although T_{CMB} plays little role in the mineral-

ogy of the lowermost mantle (see above), it plays a major role in the dynamo region, since it determines the temperature profile and structure of planetary cores. Here, we investigated the range of T_{CMB} from where the core starts crystallizing to being fully crystallized for 1 to 10 M_E Super-Earths (Figure 3).

We find the range of T_{CMB} where solid and liquid cores coexist is larger for massive Super-Earths. This effect is due to (1) the larger difference in pressure between the bottom and the top of the core for larger planets (see Figure 1) and (2) the slower increase of the core temperature relative to the Fe melting temperature. This implies that larger Super-Earths with a wide CMB temperature range over which a solid and liquid cores coexist may be more likely to have magnetic fields driven by compositional convection. The length of time the core spends in compositional convection regime depends on the core cooling rate and CMB heat flow, which should be considered in future work.

It is also interesting to note that in the T_{CMB} range where the inner core is growing, the top of the core is at temperatures close to the mantle solidus (Figure 3). As a result, for large planets a growing inner core implies a partially liquid lower mantle, which may play an important role in planetary thermal evolution and should be considered in future studies.

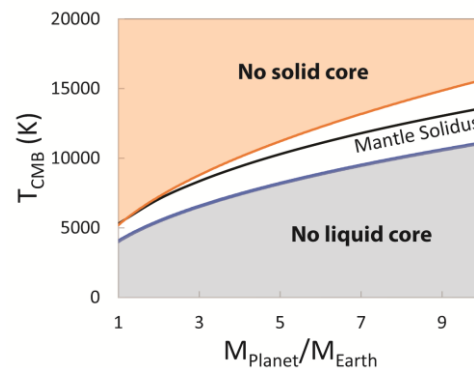


Figure 3: Temperature at the core mantle boundary, at which the Fe core starts crystallizing (below red curve) and finishes crystallizing (below blue curve). The white area shows the conditions where a solid inner core and a liquid outer are both present. The black curve indicates the temperature at the CMB, where the top of the core is at the solidus temperature of the mantle.

References: [1] Driscoll P. & Olson P. (2011) *Icarus*, 213, 12-23. [2] Umemoto K. et al. (2017) *Earth & Planet. Sci. Lett.*, 478, 40-45. [3] Tsuchiya T. & Tsuchiya J. (2011) *Proc. Of the Nat. Acad. Of Sci. of the USA*, 108, 1252-1255. [4] Ito E. & Takahashi E. (1989) *J. of Geoph. Lett.*, 94, 10637-10646. [5] Hernlund J.W. & Labrosse S. (2007) *Geoph. Res. Lett.*, 34, 1-4. [6] Stixrude L. (2014) *Phil. Trans. Of Roy. Soc. A*, 372: 20130076.