



The role of rotation in the evolution of dynamo-generated magnetic fields in Super Earths

Jorge I. Zuluaga*, Pablo A. Cuartas

Instituto de Física – FCEN, Universidad de Antioquia, Calle 67 No. 53-108, Medellín, Colombia

ARTICLE INFO

Article history:

Received 4 January 2011

Revised 8 October 2011

Accepted 18 October 2011

Available online 31 October 2011

Keywords:

Interiors

Magnetic fields

Thermal histories

ABSTRACT

Planetary magnetic fields could impact the evolution of planetary atmospheres and have a role in the determination of the required conditions for the emergence and evolution of life (planetary habitability). We study here the role of rotation in the evolution of dynamo-generated magnetic fields in massive Earth-like planets, Super Earths ($1\text{--}10 M_{\oplus}$). Using the most recent thermal evolution models of Super Earths (Gaidos, E., Conrad, C.P., Manga, M., Hernlund, J. [2010]. *Astrophys. J.* 718, 596–609; Tachinami, C., Senshu, H., Ida, S. [2011]. *Astrophys. J.* 726, 70) and updated scaling laws for convection-driven dynamos, we predict the evolution of the local Rossby number. This quantity is one of the proxies for core magnetic field regime, i.e. non-reversing dipolar, reversing dipolar and multipolar. We study the dependence of the local Rossby number and hence the core magnetic field regime on planetary mass and rotation rate. Previous works have focused only on the evolution of core magnetic fields assuming rapidly rotating planets, i.e. planets in the dipolar regime. In this work we go further, including the effects of rotation in the evolution of planetary magnetic field regime and obtaining global constraints to the existence of intense protective magnetic fields in rapidly and slowly rotating Super Earths. We find that the emergence and continued existence of a protective planetary magnetic field is not only a function of planetary mass but also depend on rotation rate. Low-mass Super Earths ($M \lesssim 2 M_{\oplus}$) develop intense surface magnetic fields but their lifetimes will be limited to 2–4 Gyrs for rotational periods larger than 1–4 days. On the other hand and also in the case of slowly rotating planets, more massive Super Earths ($M \gtrsim 2 M_{\oplus}$) have weak magnetic fields but their dipoles will last longer. Finally we analyze tidally locked Super Earths inside and outside the habitable zone of GKM stars. Using the results obtained here we develop a classification of Super Earths based on the rotation rate and according to the evolving properties of dynamo-generated planetary magnetic fields.

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1. Introduction

The number of known exoplanets in the mass range between 1 and $10 M_{\oplus}$ is growing (hereafter these objects will be called “Super Earths” or SEs following the classification by Valencia et al. (2006, 2007a)). At the time of writing, there are almost 46 confirmed planets in this mass range¹ (Rivera et al., 2005; Beaulieu et al., 2006; Udry et al., 2007; Mayor and Udry, 2008; Ribas et al., 2008; Queloz et al., 2009; Bonfils et al., 2011; Lissauer et al., 2011) and more than a few hundred SEs candidates are awaiting further analysis and confirmation (Borucki et al., 2011). These discoveries have increased the interest to model and understand the geophysical properties of this type of planets (Valencia et al., 2006, 2007a,b; Valencia and O’Connell, 2009; Seager et al., 2007; Kaltenegger,

2010; Korenaga, 2010). The habitability of SEs, in particular those similar in composition and structure to the Earth, is an interesting topic in the field and several theoretical works have paid special attention to this particular aspect of SEs properties (Grieffmeier et al., 2005, 2009, 2010; Selsis et al., 2007; van Thienen et al., 2007; von Bloh et al., 2007; Lammer et al., 2010).

Models of the interior structure of SEs have been extensively developed over the last 5 years (Valencia et al., 2006, 2007a,b; Fortney et al., 2007; Seager et al., 2007; Selsis et al., 2007; Sotin et al., 2007; Adams et al., 2008; Baraffe et al., 2008; Grasset et al., 2009). Although there are still open issues to be addressed, these models are giving us an understanding of global properties such as the mass–radius relationship and its dependence with planetary composition, as well as different geophysical phenomena such as mantle convection, degassing and plate tectonics (Olson, 2007; Papuc and Davies, 2008; Valencia et al., 2007; Valencia and O’Connell, 2009; Korenaga, 2010). Recently several authors have studied in detail the thermal evolution and magnetic field properties of this type of planets (Gaidos et al., 2010; Tachinami et al., 2011; Driscoll and Olson, 2011).

* Corresponding author. Fax: + 57 4 2195666.

E-mail addresses: jzuluaga@fisica.udea.edu.co (J.I. Zuluaga), p.cuartas@fisica.udea.edu.co (P.A. Cuartas).

¹ For updates, please refer to <http://exoplanet.eu>.

Table 1

Symbols and quantities used in this work.

Symbol	Meaning	Notes
<i>Acronyms</i>		
PMF	Planetary magnetic field	Surface magnetic field
CMF	Core magnetic field	Core surface magnetic field
CTE	Core Thermal Evolution	Gaidos et al. (2010)
MTE	Mantle based Thermal Evolution	Tachinami et al. (2011)
HZ	Habitable zone	Kasting et al. (1993)
<i>Planetary properties</i>		
R_p	Planetary radius, $R_p = 6371(M/M_\oplus)^{0.265}$	km, Valencia et al. (2006)
R_c	Radius of the core, $R_c = 3480(M/M_\oplus)^{0.243}$	km, Valencia et al. (2006)
$\bar{\rho}_c$	Average core density, $\bar{\rho}_c = 1.1 \times 10^4 (M/M_\oplus)^{0.271}$	kg m ⁻³ , Valencia et al. (2006)
Ω, T	Rotation rate, period of rotation, $T = 2\pi/\Omega$	rad s ⁻¹ , days
R_{ic}, χ	Radius of the solid inner core, $\chi = R_{ic}/R_c$	km
D	Vertical height of the liquid core, $D = R_c - R_{ic}$	km
V	Volume of the dynamo region, $V = 4/3\pi(R_c^3 - R_{ic}^3)$	km ³
<i>Dynamo properties</i>		
Q_{conv}	Total convective power	W s ⁻¹
p	Total convective power density	Adimensional
Lo	Lorentz number, $Lo \sim < E_{mag} >^{1/2}$	Adim., Christensen and Aubert (2006)
Ro	Rossby number, $Ro \sim < E_{kin} >^{1/2}$	Adim., Christensen and Aubert (2006)
Ro_l	Local Rossby number, $Ro_l \sim < l_u > < E_{kin} >^{1/2}$	Adim., Christensen and Aubert (2006)
f_{ohm}	Fraction of ohmic dissipation	Adim., Christensen and Aubert (2006)
<i>Magnetic field properties</i>		
B_{rms}	rms Amplitude of the magnetic field inside the convecting shell	μT
$\bar{B}_{dip}$	Dipolar component intensity of the CMF	μT
$\bar{B}_{s,dip}$	Dipolar component of the PMF, $\bar{B}_{s,dip} = \bar{B}_{dip}(R_c/R_p)^3$	μT
f_{dip}	Dipolar fraction of the CMF, $f_{dip} = \bar{B}_{dip}/\bar{B}_{CMB}$	Adim., Christensen and Aubert (2006)
b_{dip}	Ratio between the rms strength of the field and the dipolar component at the CMB, $b_{dip} = B_{rms}/\bar{B}_{dip}$	Adim., Christensen et al. (2009)
t_{ic}	Starting time for the inner core nucleation	Gyrs
T_{dip}	Dipolar lifetime	Gyrs
t_{sw}	Dipolarity switch time	Gyrs
T_{dyn}	Dynamo lifetime	Gyrs

Planetary magnetic fields would likely play a role in planetary habitability (von Bloh et al., 2007; Grießmeier et al., 2005, 2009, 2010; van Thienen et al., 2007; Lammer et al., 2010). Understanding the conditions for the emergence and long term evolution of a protective planetary magnetic field (hereafter PMF) is crucial to evaluate the complex conditions for habitability of SEs. The same conditions could also be applied to evaluate the habitability of exomoons around extrasolar giant planets (Kaltenegger et al., 2010).

The current understanding of PMF emergence and evolution in SEs arises from thermal evolution models for the Earth (Stevenson, 2003; Labrosse, 2003, 2007a,b; Nimmo, 2009; Aubert et al., 2009; Breuer et al., 2010) and scaling laws for convection-driven dynamos obtained from extensive numerical simulations (Christensen and Aubert, 2006; Olson and Christensen, 2006; Aubert et al., 2009; Christensen et al., 2009; Christensen, 2010). Two recent works studied the problem of PMF evolution in SEs by developing detailed models of planetary thermal evolution (Gaidos et al., 2010; Tachinami et al., 2011). Both works have paid special attention to different but complementary aspects of the problem. Gaidos et al. (2010) uses a model of the structure of the planetary core and its thermal evolution (hereafter the *Core Thermal Evolution* or *CTE model*). On the other hand Tachinami et al. (2011) uses the Mixing Length Theory adapted to planetary conditions to model mantle convection with a detailed treatment of its rheological properties (hereafter the *Mantle based Thermal Evolution model* or *MTE model*). Although thermal evolution models for the Earth, other terrestrial planets and even SEs have been developed in the past (Stevenson, 2003; Labrosse, 2003, 2007a; Papuc and Davies, 2008; Nimmo, 2009; Breuer et al., 2010), the CTE and MTE models give the first detailed description aimed at studying dynamo-generated magnetic fields of extrasolar terrestrial planets.

We use the results of the CTE and MTE models to study the role of rotation in the evolution of PMF in SEs. We focus on the

evolution of the regime of the core magnetic field (CMF) which can be broadly classified as non-reversing dipolar, reversing dipolar and multipolar. For this purpose we compute the *local Rossby number*, one of the proxies for CMF regime, as a function of the rotation period and planetary mass. Using this property we predict the long term evolution of the surface PMF in rapidly and slowly rotating planets.

In Section 2 we summarize the most important results of the CTE and MTE models. Section 3 presents the scaling laws for convection-driven dynamos used to predict the properties of the CMF. In Section 4 we present a general procedure to compute the CMF intensity in the dipolar and multipolar regimes including an implicit dependence on rotation rate. In Section 5 we present the results of applying the procedure devised here to predict the maximum dipolar component of the field in SEs with different periods of rotation and thermal histories as predicted by the CTE and MTE models. Section 6 is devoted to discuss the limitations of our procedure and the implications of our results. A summary, concluding remarks and future prospects are presented in Section 7. For reference a list of the symbols and the physical quantities used in this work are presented in Table 1.

2. Thermal evolution models of SEs

2.1. Planetary thermal evolution

The evolution and long-term survival of a dynamo-generated PMF² strongly depends on the thermal history of the planet. The

² It is important to stress that we are considering in this work magnetic fields generated by dynamo action in a liquid metallic core. Other fluid shells (liquid, ice or gaseous mantles) may sustain other type of dynamos out of the scope of this work.

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