Magnetic Fields in Earth-like Exoplanets and Implications for Habitability of Planets Around M-dwarfs

Mercedes López-Morales
(CSIC-IEEC, CIW-DTM)

Natalia Gómez-Pérez & Thomas Ruedas

Gómez-Pérez, López-Morales & Ruedas (2011)

M-dwarfs as planet hosts

- Tarter et al. 2007 and Scalo et al. 2007 recommended M-dwarfs as best targets to search for exo-Earths.

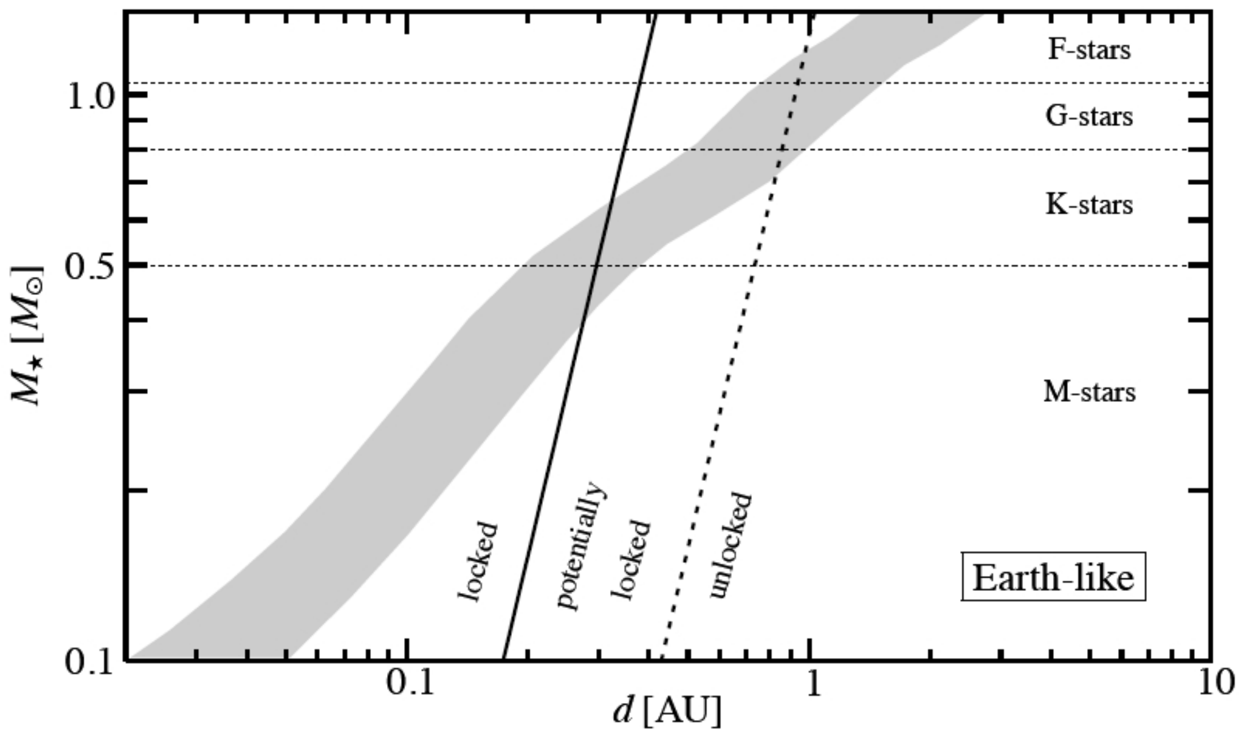
  - **$M_{st} < 0.5\ M_{sun}$**
  - **R_p / R_{st} and M_p / M_{st}** $\uparrow\uparrow$
  - **Signal of small planet around small star** $\uparrow\uparrow$

Idea confirmed by discovery of over 20 planets around M-dwarfs, e.g. GJ 436b (Butler et al. 2004) and GJ 1214b (Charbonneau et al. 2009)

Can planets around M-dwarfs be habitable?

1) M-dwarfs are more active than Sun-like stars → Planets will be exposed to denser winds

2) M-dwarfs' Habitable Zones are 10 times closer to the star than for Sun-like stars → Planets are tidally locked, are in synchronous rotation and have weak magnetic moments



(Grießmeier et al. 2009)

Can planets around M-dwarfs be habitable?

1) M-dwarfs are more active than Sun-like stars → Planets will be exposed to denser denser winds

2) M-dwarfs' Habitable Zones are 10 times closer to the star than for Sun-like stars → Planets are tidally locked, are in synchronous rotation and have weak magnetic moments

The rotation of the planet is not necessarily synchronized to the star if the planet's orbit is eccentric (Correia et al. 2008; Barnes et al. 2009)

Yes, but maybe not as weak as we thought.

Planetary Science-Astronomy need more communication

Early model attempts

Blackett (1947) $M \sim L$

Busse (1976) $M \sim \rho^{1/2} r^4 \Omega$

Stevenson (1983) $M \sim \rho^{1/2} r^3 \Omega^{1/2}$

Curtis & Ness (1986) $M \sim \rho^{1/3\,2} r^{7/2} \Omega^{1/2} F^{1/6}$

ISAS-1 (1992) $M \sim \rho^{1/2} r^{7/2} \Omega^{3/4}$

ISAS-2 (1992) $M \sim \rho^{1/2} r^3 \Omega^{1/2}$

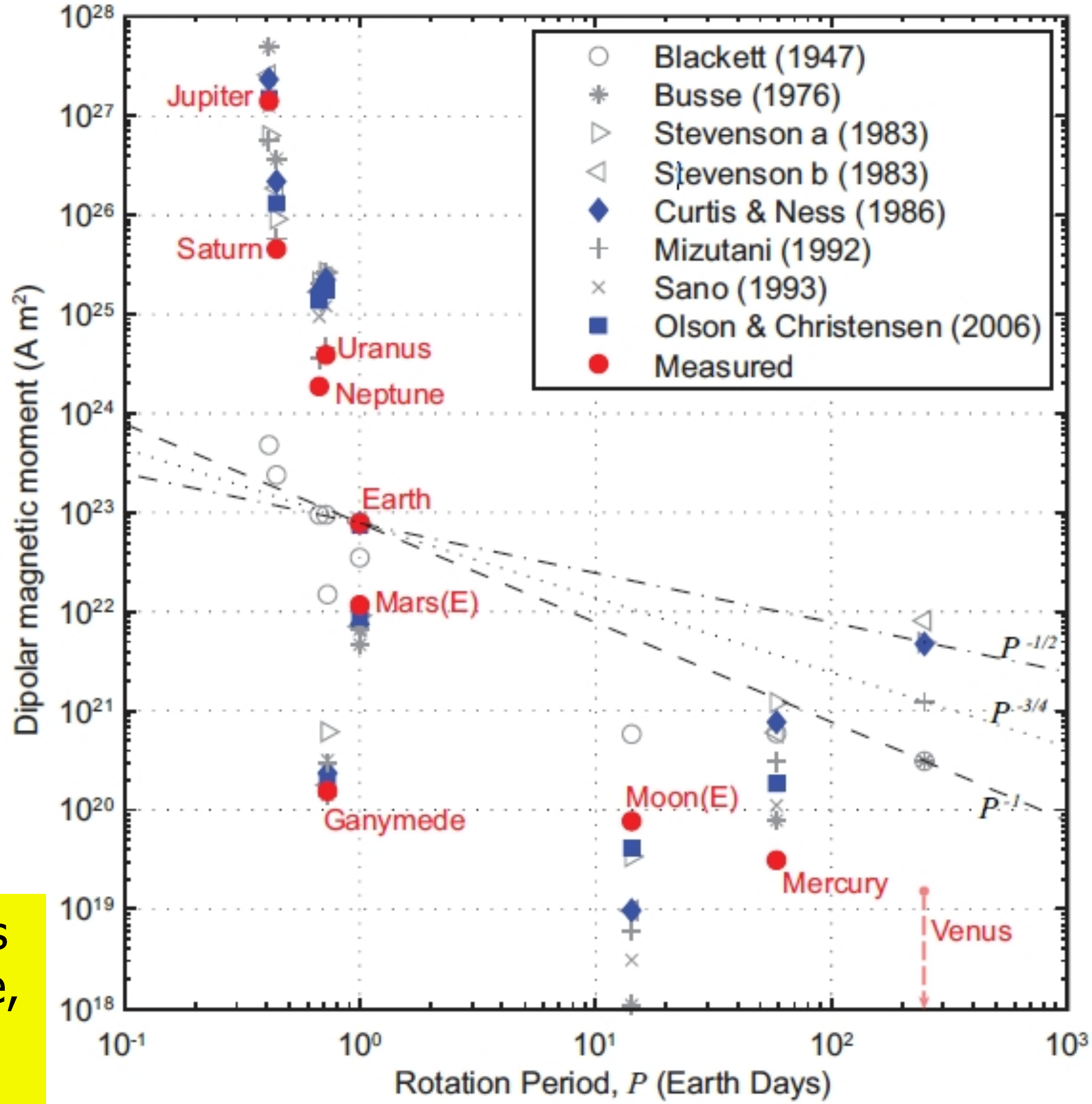
Sano (1993) $M \sim \rho^{1/2} r^{7/2} \Omega$

New numerical models

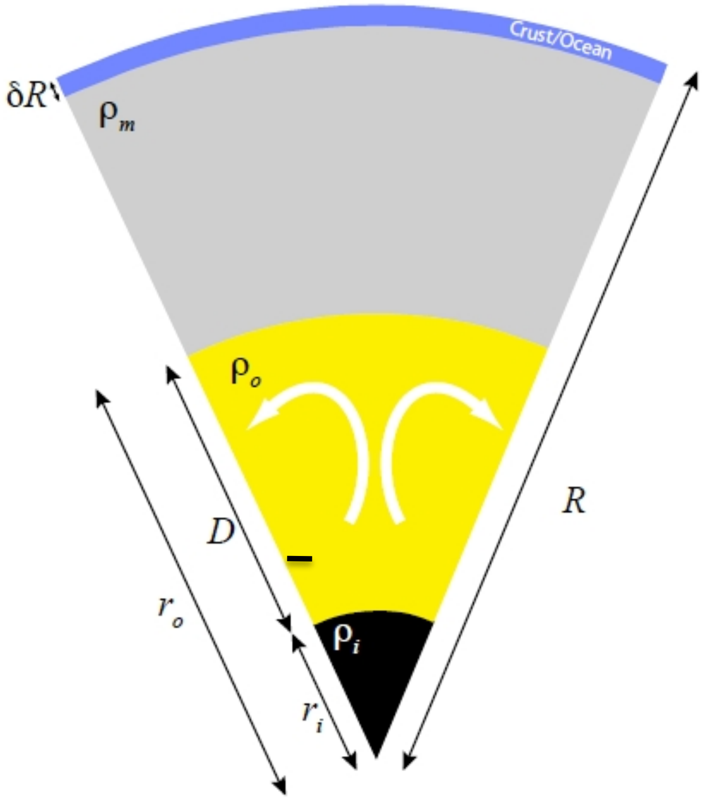
Olson & Christensen (2006)

$$M \sim 4\pi\, r_o^3\, \gamma\, (\bar{\rho}_o\, \mu_o)^{1/2}\, (F\, D)^{1/3}$$

The OC2006 scaling law mispredicts observations by < 15%, on average, while other laws give average mispredictions between 20 – 268%.



Exo-Earths magnetic moment models using OC2006



$$M \sim 4\pi\, r_o^3\, \gamma\, (\bar{\rho}_o\, \mu_o)^{1/2}\, (F\, D)^{1/3}$$

M = Magnetic moment

r_o = planetary core radius

γ = fitting coefficient (=0.1-0.2)

$\bar{\rho}_o$ = bulk density of fluid in convective zone

μ_o = magnetic permeability of vacuum

F = average convective buoyancy flux

D = thickness of the convection cell

- r_i/D decreases with age
- we currently do not know how F changes with age

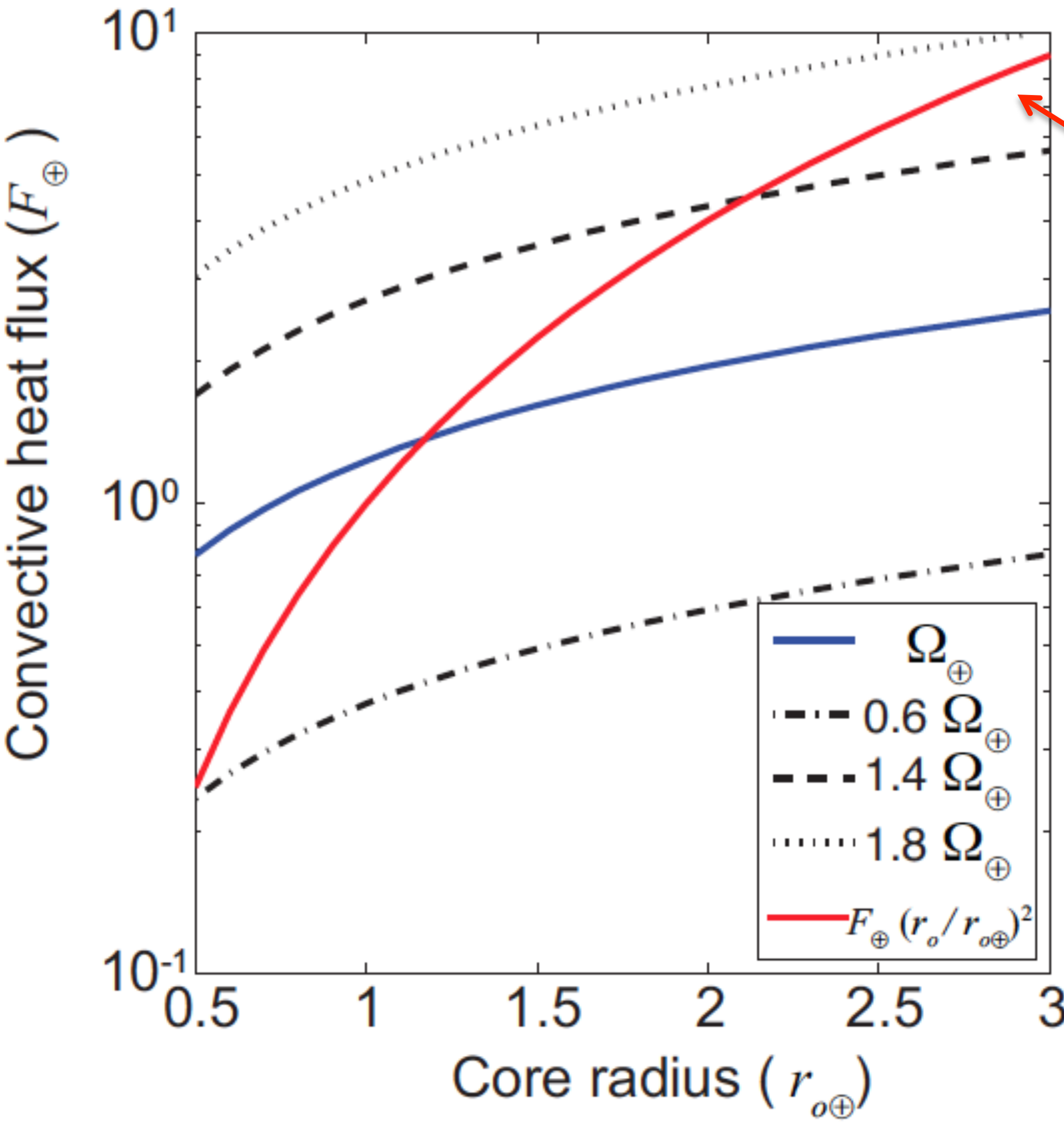
$$\frac{F}{F_\oplus} < \left(\frac{Ro_l^*}{Ro_{l\oplus}} \left(\frac{D}{D_\oplus}\right)^{1/3} \left(\frac{\Omega}{\Omega_\oplus}\right)^{7/6} \right)^2 \longrightarrow$$

- If $Ro_l \leq 0.1 \longrightarrow F$ generates dipolar dynamo
- If $Ro_l > 0.1 \longrightarrow F$ generates multipolar dynamo

** $Ro_l = 0.1$ ($=Ro_l^*$) gives F_{max} for $M_{dipolar}$

** $M_{multipolar} = 5 \times 10^{-2}\, M_{dipolar}$

F as a function of planetary rotation rate



F for the most efficient dynamo, i.e. $F \propto r_o^2$, which corresponds to D = 0.65 r_o (Heimpel et al. 2005).

Depending on the rotation rate of the planet and its core radius, the most efficient dynamo for the planet can be either a dipole or a multipole.

- For fast rotators → dipole
- For slow rotators → multipole

** core radii range equivalent to 0.5 -12 M_{earth} planets, assuming same interior composition as Earth.

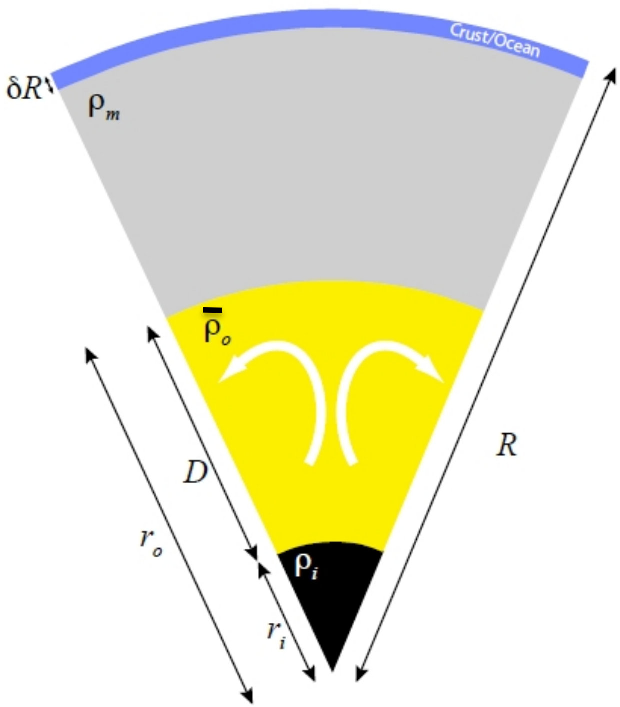
Exo-Earths interior models

$$\frac{d\rho}{dr} = \frac{-G\,\rho(r)\,m(r)}{r^2\,\phi(r)},$$
$$\frac{dm}{dr} = 4\pi\,r^2\,\rho(r),$$
$$\frac{dP}{dr} = -\rho(r)\,g(r),$$
$$\frac{dg}{dr} = 4\pi\;G\,\rho(r) - \frac{2\,G\,m(r)}{r^3},$$

$$\phi(r) = \frac{1}{3\rho_0}(1-2\varepsilon)\left(C_1\,(1-7\varepsilon) + C_2(\varepsilon - 9/2\,\varepsilon^2)\right)$$

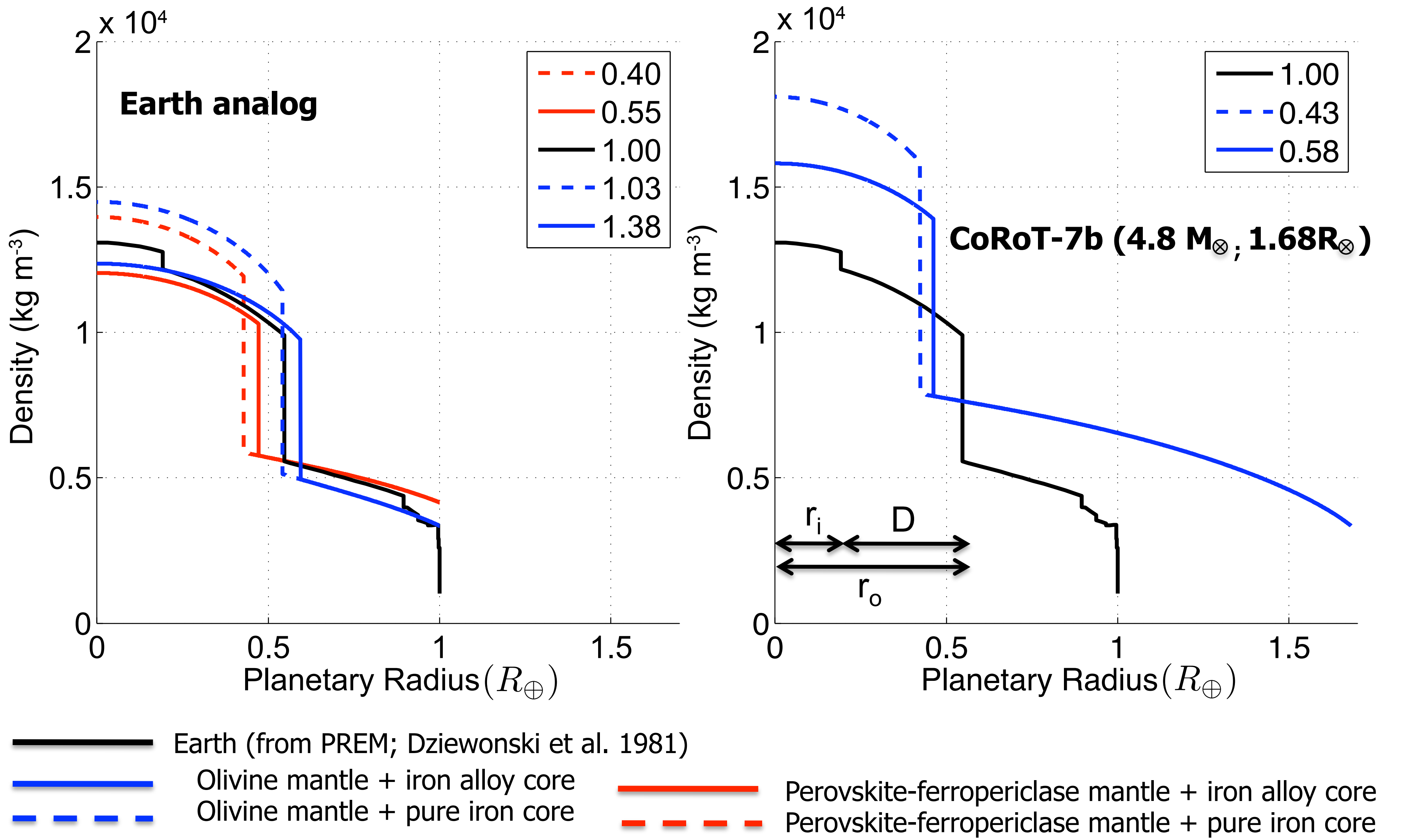
$$\varepsilon = 1/2\,\left(1-(\rho(r)/\rho_0)^{2/3}\right),\; C_1 = 3\,K_{S0},\; C_2 = 9\,K_{S0}\,(4-K'_{S0})$$

Additional assumptions: $D=0.65r_o$ and $r_i/r_o = 0.35$ and F is constant with time.

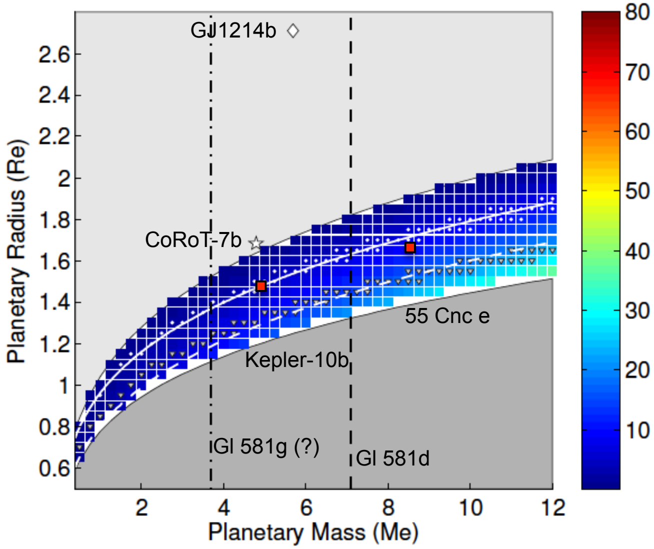


Region	Materials	ρ_0 (kg m^{-3})	K_{s0} (GPa)	K_{s0}'
Core	Pure iron (Fe)	8300	160.2	5.820
Core	Iron alloy (FeS)	7171	150.2	5.675
Mantle	Pure olivine ($Mg_{1.8}Fe_{0.2}SiO_4$)	3347	126.8	4.274
Mantle	Perovskite + Ferropericlase ($Mg_{0.9}Fe_{0.1}SiO_3$ + $Mg_{0.9}Fe_{0.1}O$)	4152	233.6	4.524

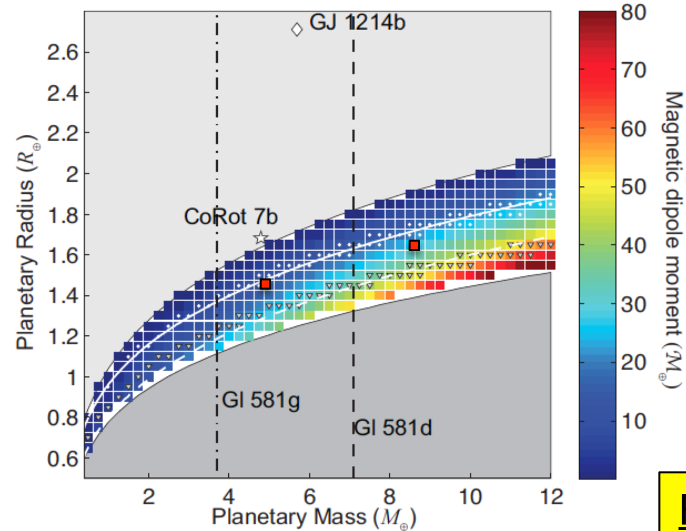
Radius-Density Profiles

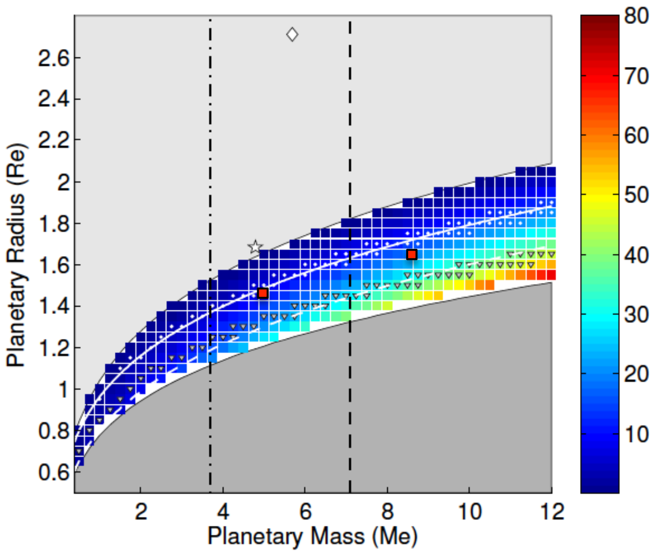


Our magnetic moment estimate for exo-Earths

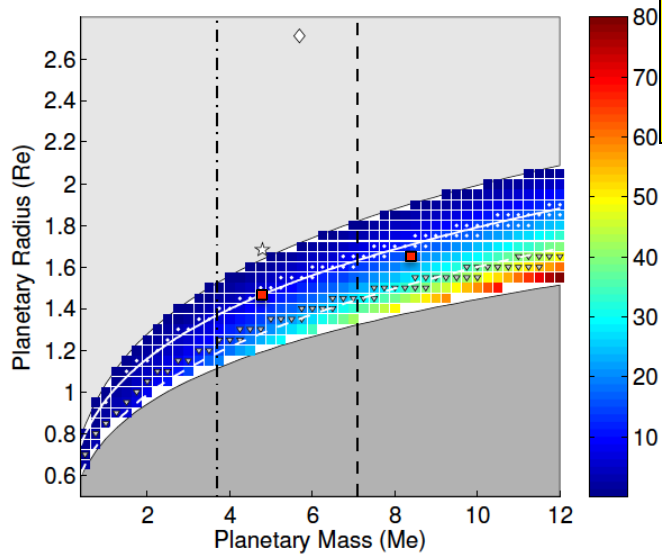


(a) Rotation rate 0.6 Ω_{earth}





(c) Rotation rate 1.4 Ω_{earth}



(d) Rotation rate 1.8 Ω_{earth}

<u>Rotational velocities:</u>

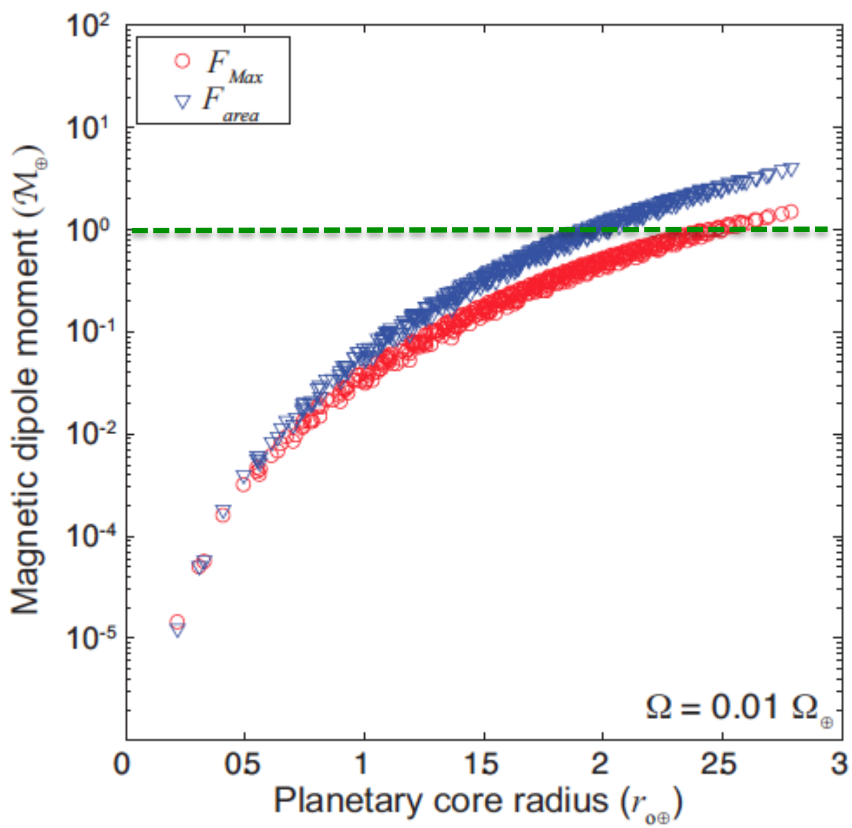
- 55 Cnc e ~ 1.35 Ω_{Earth}
- CoRoT-7b ~ 1.17 Ω_{Earth}
- Kepler-10b ~ 1.2 Ω_{Earth}
- GJ 1214b ~ 0.63 Ω_{Earth}

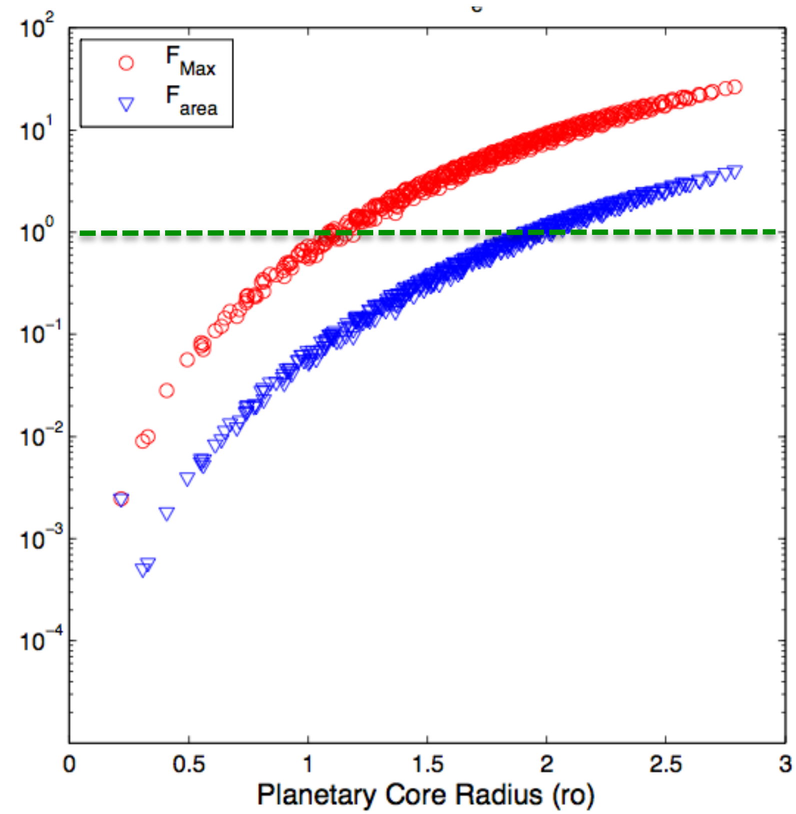
Planets in the Habitable Zone of M-dwarfs

- $\Omega \sim 0.01 - 0.02\ \Omega_{earth}$ for 0.5 M_{sun} star.
- $\Omega \sim 0.24 - 0.41\ \Omega_{earth}$ for 0.1 M_{sun} star.

○ Solution for F_{max} generating dipole (O&C 2006)

▽ Solution for $F \propto r_o^2$, multipole = 5 x 10^{-2} $M_{dipolar}$





Note that core radii range is equivalent to 0.5 -12 M_{earth} planets, assuming same interior composition as Earth.

Summary

- The magnetic moment of a planet depends on its rotation rate, but also, on its chemical composition and the efficiency of convection in its interior (F)

- If a planet is rotating ‘fast enough’, Ω only marks if the dynamo is dipolar or multipolar, but magnetic moment strength will not explicitly depend on rotation.

- Some *rocky planets* might have strong magnetic fields, and therefore their surfaces will be protected against stellar and cosmic irradiation.

- In the particular case of planets in the habitable zone of M-dwarfs, even the slowest rotators might have magnetic dipolar moments stronger than Earth, and therefore have a strong enough magnetic field to shield their surface. This is most likely, however, for planets with $r_o \geq r_{o\ Earth}$.

CAUTION:

- Our current models do not account for changes of F and D with age (See poster H.08)

- Planets under extreme conditions, i.e. highly inhomogeneous heating or under very strong stellar winds, will have their magnetic field affected.

-This is still work in progress and a better understanding of the interior structure and energy transportation mechanisms in rocky planets is still necessary.