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A Magnetic Habitable Zone?

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SUMMARY

We revisit the problem of the habitability on Earth-like planets conditioned by the properties of the planetary magnetic field (PMF).

Using detailed thermal evolution models for Super Earths (GA10, TA10) and scaling laws derived from numerical dynamo experiments (Ca06, AUB09), we computed the evolving properties of the PMF.

Using a time dependent magnetic field model (ZU11) (other models use static PMFs), we computed "proxies" to magnetic habitability for tidally locked and unlocked planets in the Classical Habitable Zone (CHZ).

We introduced a new "Exposure Index" to characterize the habitability of Super Earths conditioned by PMF properties and study the "magnetic habitability landscape" in a mass-period and mass-mass diagrams.

"MAGNETIC HABITABILITY"

What has been done? (1) Models for the interaction between the planetary magnetosphere and a time dependent stellar wind (GR05, GR09).

(2) Description of the effects that the absence of a magnetic field has on planetary habitability (LA10)

(3) Analysis of the relationship between (1) and (2): planetary habitability of tidally locked planets (GR09)

Limitations: (a) Scaling laws for dipolar moments independent of thermal evolution

(b) Analysis independent of planetary mass.

What we wanted to do? We want to improve the way the properties of the PMF are computed: (1) by scaling dynamo properties using results from numerical dynamo experiments (CA06, AUB09, C10), (2) by considering the effect of the thermal evolution, (3) by introducing the dependence on rotation rates using the procedure in (ZU11).

What we did? (1) We computed the values of "magnetic habitability" proxies (dipolar moments, standoff distances) for planets in the CHZ, (2) we identified noticeable differences between static PMF models and our time dependent models, (3) we proposed a new quantity, ***Exposure Index* (*Im*)**, inspired in other phenomenological quantities, to measure the level of exposure of a planet to the stellar wind effects and cosmic rays, (4) by using Im we explored the "magnetic habitability landscape" in the planetary parameter space and identified the magnetic conditions more suitable for habitable environments in Earth-like planets (Magnetic Habitable Zone?)

SCALING LAWS FOR CONVECTION DRIVEN DYNAMOS

Classical scaling laws for numerical dynamos were developed with a low rotation rate dependence and without any thermal evolution. We found that the dipolar moment component has a stress dependence of rotation obtained from the PMF regime which is predicted by the value of the Local Rossby Number (ZU11).

$$\mathcal{M} \propto \rho c^{1/2} \omega r_c^4 \quad (Busse, 1976)$$
$$\mathcal{M} \propto \rho c^{1/2} \omega^{1/2} r_c^3 \sigma^{-1/2} \quad (Stevenson, 1983)$$
$$\mathcal{M} \propto \rho c^{1/2} \omega r_c^{7/2} \quad (Sano, 1993)$$

$$Lo \equiv \frac{B_{rms}}{\sqrt{\bar{\rho}_c \mu_o}\Omega D} = c_{Lo} f_{ohm}^{1/2} p^{1/3}, \; p = \frac{Q_{conv}}{\Omega^3 D^2 \rho V}$$
$$Ro_l \equiv \frac{U_{rms}}{\Omega L} = c_{Rol}\, p^{1/2} E^{-1/3} (Pr/Pm)^{1/5}$$

$$f_{dip} = \frac{\bar{B}_{dip}}{\bar{B}_{cmb}}, \; b_{dip} = \frac{B_{rms}}{\bar{B}_{dip}}.$$

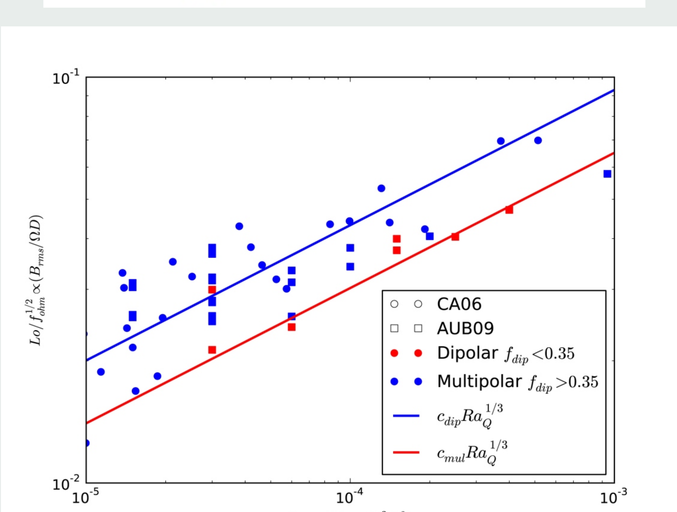

Fig.1. Magnetic field intensity scales with convective power (dipolar and multipolar)

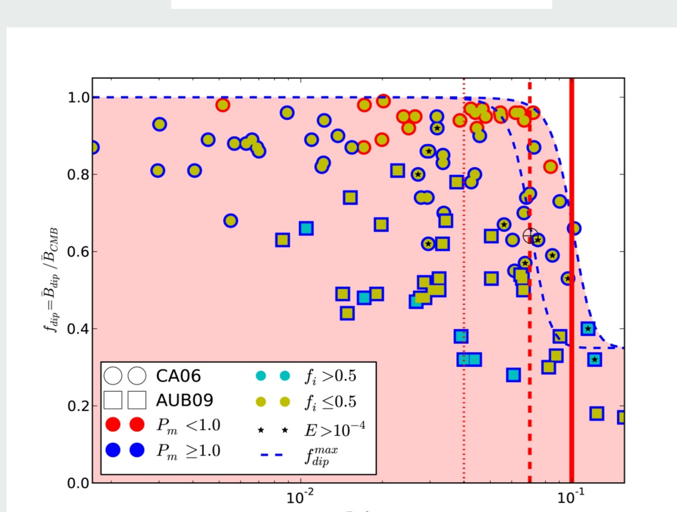

Fig.2: The PMF regime is predicted by the local Rossby Number

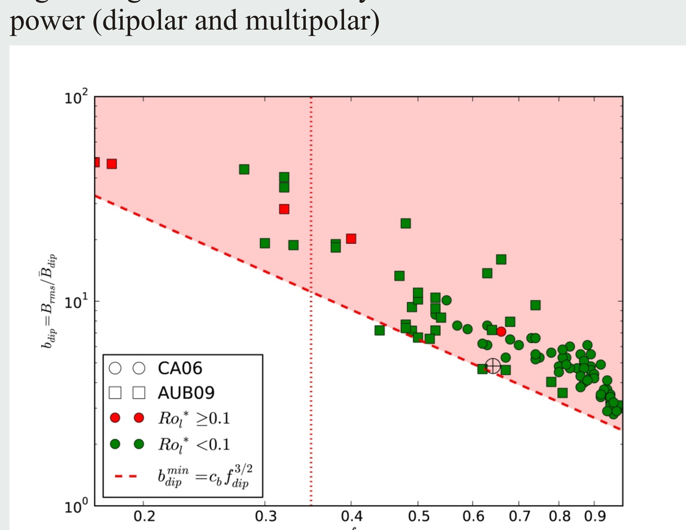

Fig.3: All numerical dynamos are above a minimum level of bdip

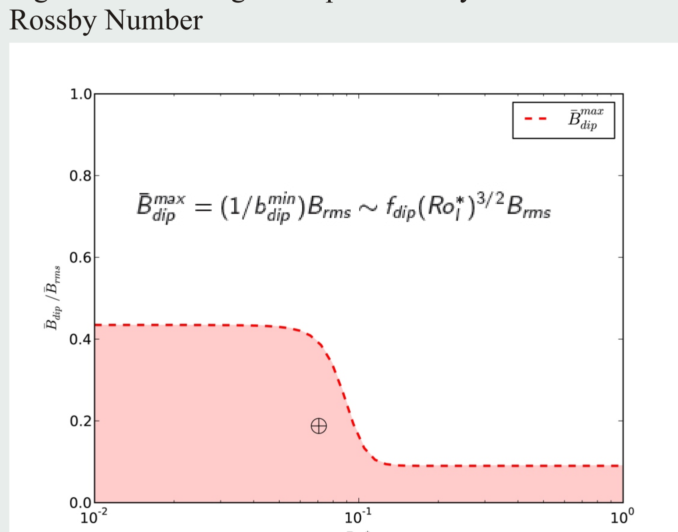

Fig.4: The maximum dipolar component of the CMF could be estimated from the local Rossby Number

THERMAL EVOLUTION MODELS

Thermal evolution models have been developed in recent years (GA10, TA10). The most rigorous model for the thermal core evolution was developed by GA10. We chose this thermal evolution model for SE's assuming tectonic activity and applying proper scaling laws for the dipolar moment (Mdip). These laws take into account the effect of planetary rotation rate (ZU11).

The main result of this model is that the inner core only grows for Mp<2 ME. For Mp>2 ME a solid core never grows and remain liquid until suppressed by the convective power.

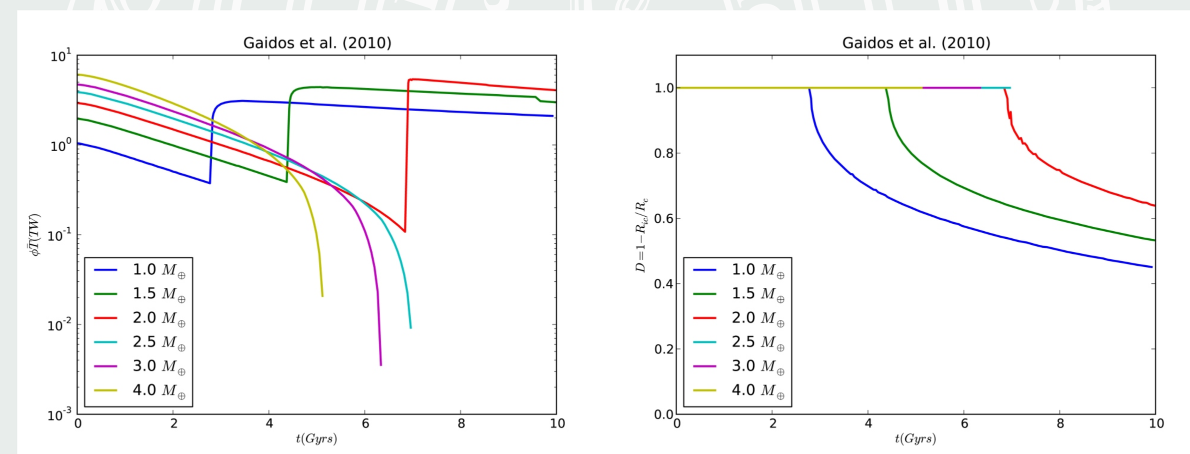

Fig.5: Power convection for low mass planets increases with the inner core growth

PROXIES TO MAGNETIC HABITABILITY

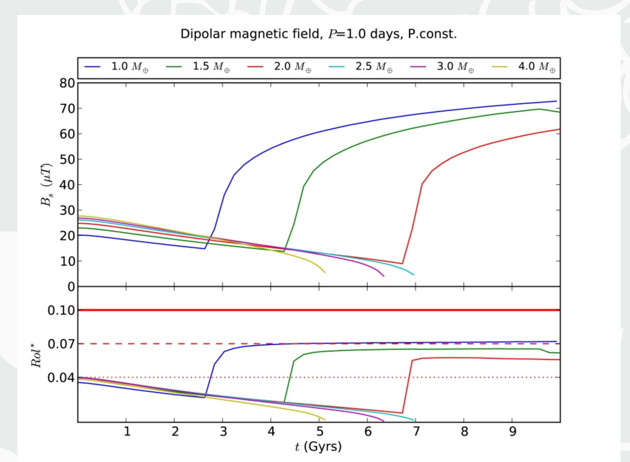

Fig.6: The PMF intensity at the planet surface is greater for low mass planets after inner core growth

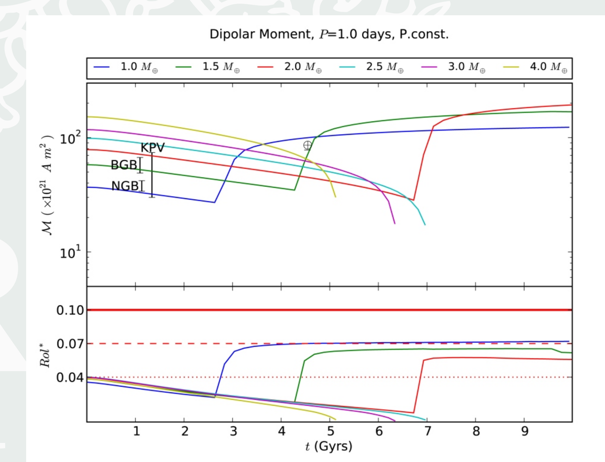

Fig.7: Dipolar moment intensity for a 1 M⊕ is in range of values for the paleo-magnetic field (TD11)

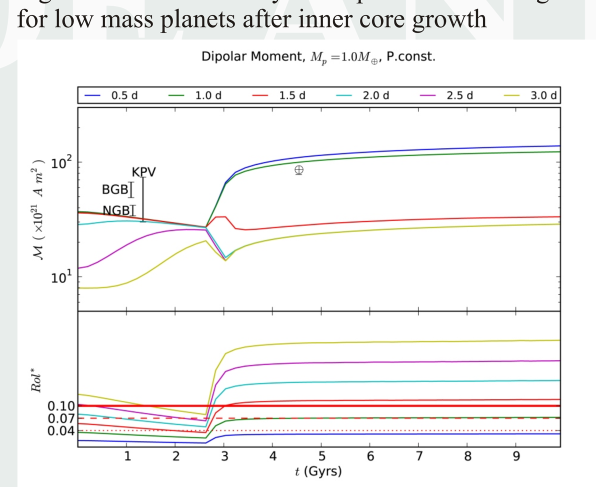

Fig.8: For a 1 M⊕ the dipolar moment depends on the rotation periods.

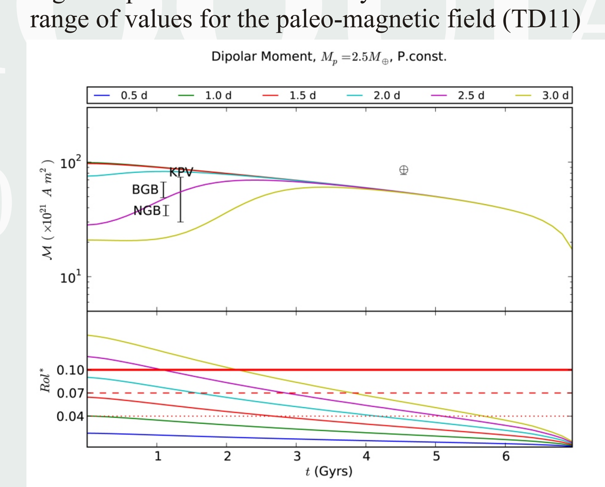

Fig.9: For a more massive Earth-like planet the dipolar moment falls down with time

The planetary magnetosphere acts as a shield against the stellar wind and cosmic rays impact (GR05, GR09, Lammer et.al. 2010). The key properties of magnetic habitability are related to the intensity of the dipolar magnetic moment. These models assumed simple magnetic moment dependence and no thermal or magnetic evolution at all.

Standoff distance:
$$R_s \sim \mathcal{M}^{1/3}(nv_{eff}^2)^{-1/6} \quad (Martyn\ et.al., 1951)$$
Co − latitud of the polar cap:
$$\cos(\phi_P) \sim \mathcal{M}^{1/6}(nv_{eff}^2)^{-1/12} \quad (Siscoe\ et.al., 1975)$$
Magnetopause field:
$$B_{mp} \sim (nv_{eff}^2)^{-1/12} \quad (Siscoe\ et.al., 1975)$$
Unmagnetized mass loss rate:
$$\dot{M}_a \sim nv_{eff} \quad (Canto\&Raga, 1991)$$

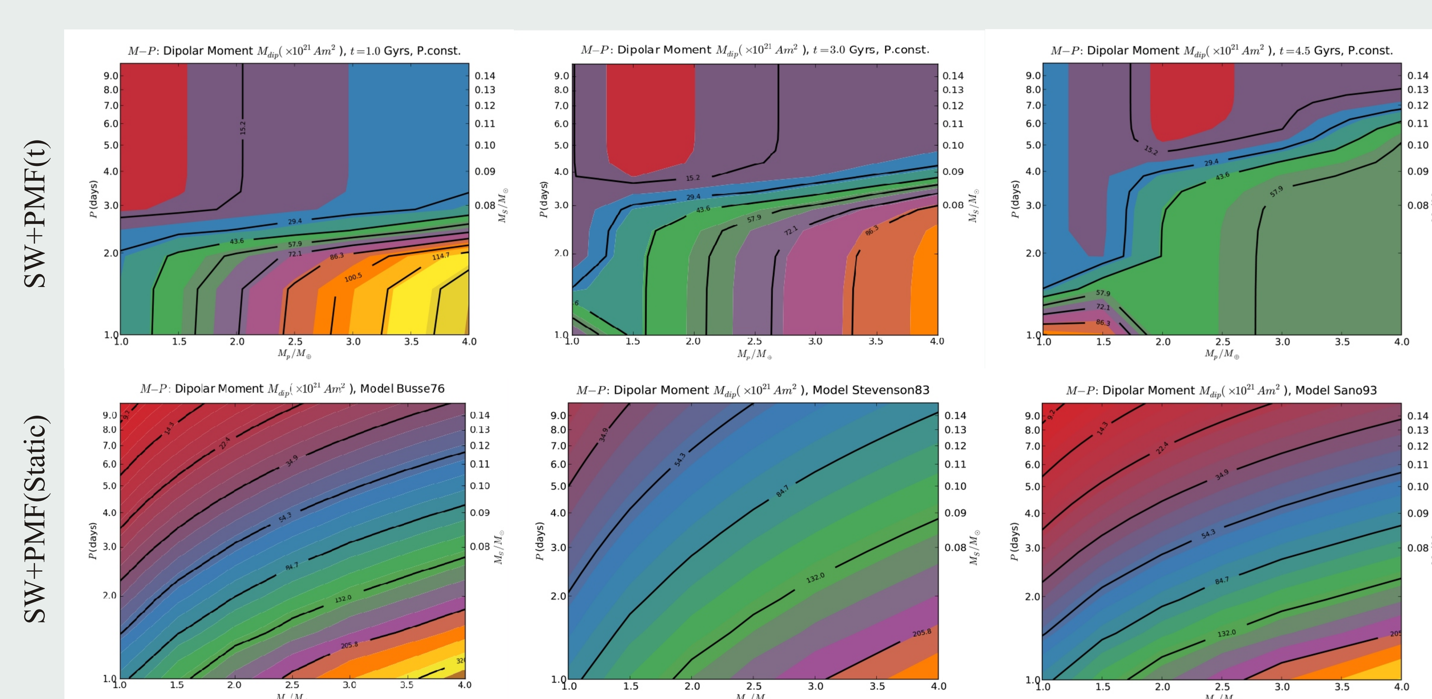

Fig.10: Upper panel, dipolar moment change through the time (ZU11b). Lower panel, dipolar moment evolving monotonous (GR07).

RESULTS

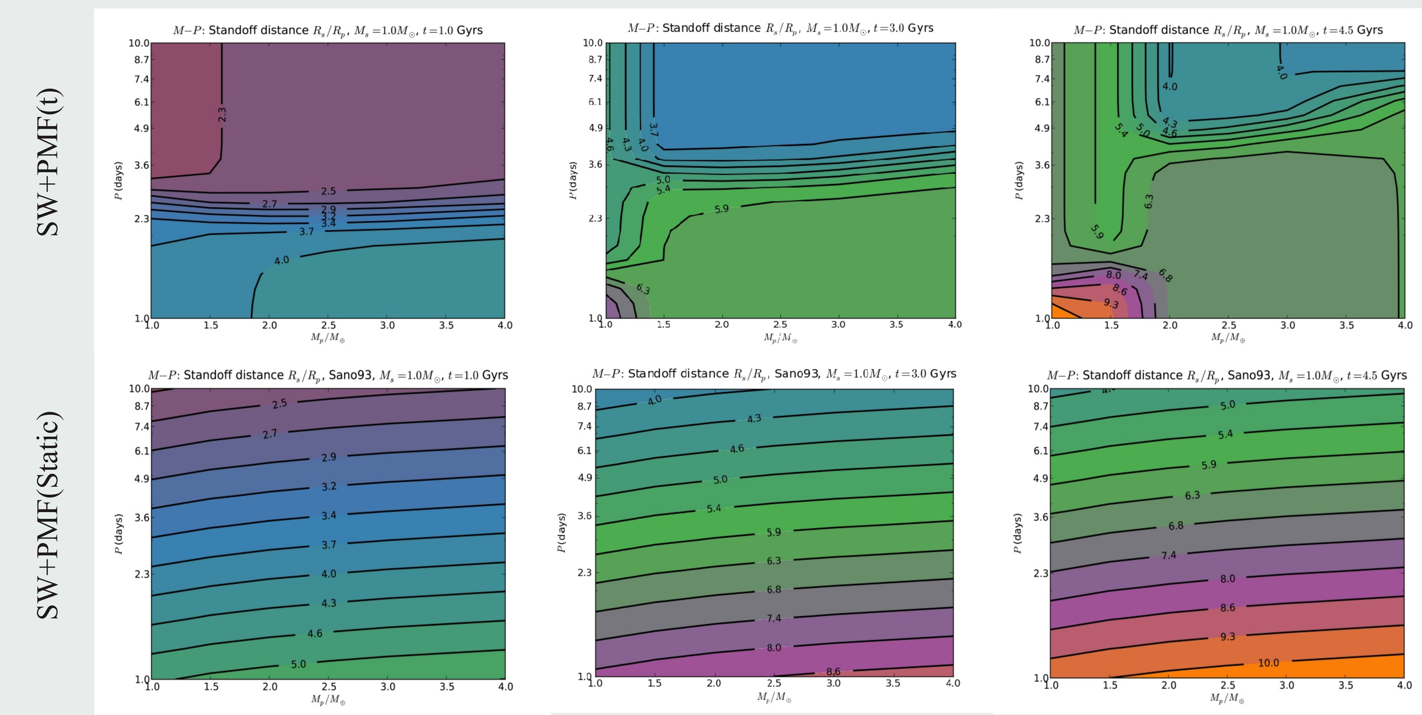

Fig.11: Upper panel, standoff distance change through time (ZU11b). Lower panel, standoff distance evolves monotonously for static models (GR07).

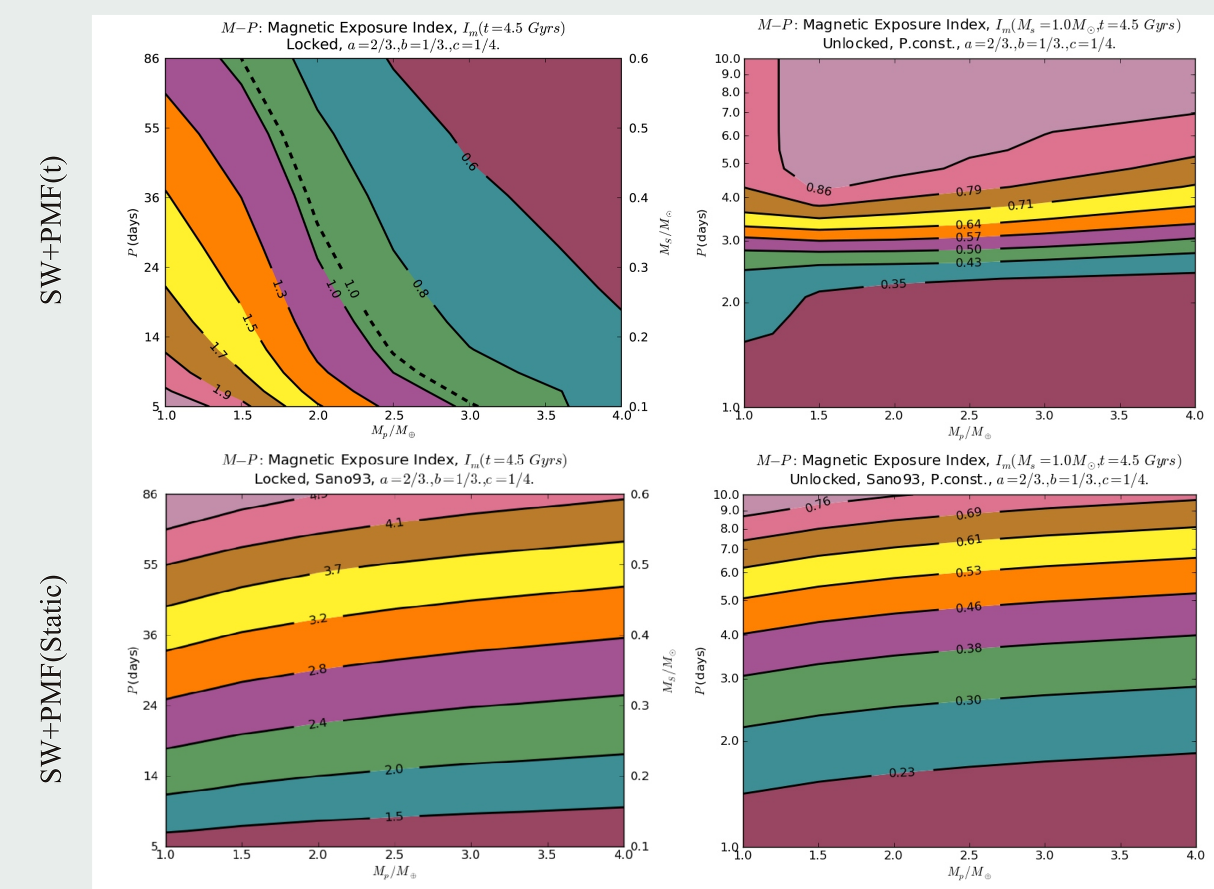

Fig.12: Upper panel, the exposure index varies differently for locked and for unlocked planets (ZU11b). Lower panel, the variation of the index is again monotonous.

$$I_m \approx \int_{t_0}^{t} \mathcal{M}^{-a}(nv_{eff}^2)^b M_p^{-c}\, dt$$

Based on the "magnetic habitability" proxies, we computed the value of a new phenomenological inspired quantity ***Im*** for planets in the CHZ of K8+ stellar types (Ms<0.6 Msun), and CHZ for stars 0.6-1.0 Msun, where all planets have higher rotation rates.

In general ***Im=Im(t, P, d, Mp, Ms).***

For a fixed ***t*** = 4.54 Gyrs, ***Im=Im(Mp, P, Ms , d).***

For planets in the CHZ, ***d = d(Ms):***

- Tidally locked planets, ***P = P(d), Im(Mp, Ms).***
- Unlocked planets, ***Im(Mp, P, Ms).***

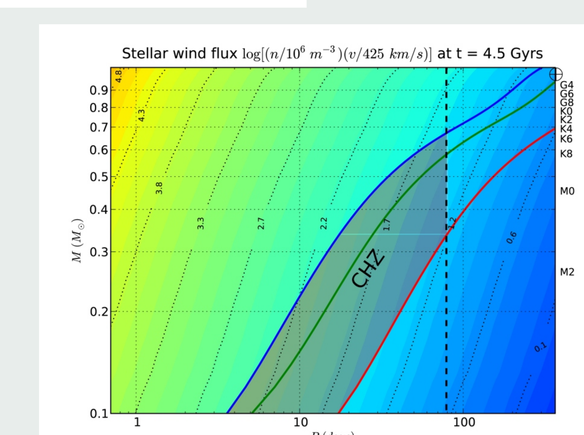

Fig.13

Conclusions

- We studied the conditions for magnetic habitability considering the evolution of Stellar Wind and PMF.
- We found differences with the static PMF models. These differences points in the direction that thermal evolution models should be addressed in the MH problem.
- We proposed a metric to quantify the level of exposure to external agents affecting the habitability and introduced a phenomenological ansatz.
- We studied the relative exposure index of locked and unlocked planets in the CHZ.
- Regions of better conditions for planetary habitability have been identified in this preliminary approach.

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