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# Planetary Magnetism as a Parameter in Exoplanet Habitability

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## Abstract

Here, we investigate the hypothesis that planetary magnetism has a significant effect on the maintenance of liquid water on an exoplanet by determining which of the currently detected planets have sufficient magnetosphere protection from cosmic and stellar irradiation. We used Olsen & Christiensen's model [1] to determine the maximum magnetic dipole moment of terrestrial exoplanets, further analyzing those located in the Circumstellar Habitable Zone (CHZ). Our results indicate that 70% of exoplanets currently defined as potentially habitable (rocky planets located in the CHZ), even with the best-case scenario of modelling the maximum possible dipole moment with the lowered magnetic protection threshold value of $0.55 M_{\oplus}$, would not have a magnetic field strong enough to protect their surface, and consequently any potential water or life on it, against stellar and cosmic irradiation.

## 1. Introduction

Within the next decade upcoming observations with near-future telescopes, will provide us with ever-increasing number of planets. In order to make the most of the limited observational resources available, optimal target selection will be of the utmost importance. Selection of targets currently relies on "classically" defined habitable zone, constrained only by the density of the planet and the distance from its host star. More than ever it is important to expand to a multi-parameter approach and include factors such as magnetic field, albedo, tidal locking, impact events, and plate tectonics. This multi-parameter approach to habitability (M-PAtH) will enable us to rank the current habitable worlds and provide a justified priority of those most likely to maintain liquid water (and host life) in order to best utilize telescope time when biosignature observations become a possibility.

The majority of our assessments on habitability stems from what we have observed in our own solar system. One of the differences between Earth and Mars/Venus is the presence of a strong magnetic dipole moment that protects the surface and is hypothesized to shield surface liquid water from solar winds and flares [2]. Venus, Earth and Mars likely began with similar amounts of water since they are all about the same size and formed at the same time (~4.5 billion years ago) [3]. This is corroborated by their Deuterium to Hydrogen ratios (D/H) displayed in Table 1 which suggests that both Mars and Venus had more water early in their histories. Yet today, only Earth has managed to retain most of its water.

Table 1: Atmospheric loss and isotope ratios

| Planet | D/H ratio ($\times 10^{-4}$) |
|---|---|
| Venus | $160 \pm 20$ |
| Earth | $1.49 \pm 0.03$ |
| Mars | $9.24 \pm 1.66$ |

In the absence of sufficient magnetic protection, the upper atmosphere of an exoplanet will be directly exposed to stellar winds and coronal mass ejections, resulting in atmospheric mass-loss due to non-thermal processes such as ion pickup, photo-chemical energizing mechanisms, and sputtering [4]. Since, planetary magnetism and the parameters of stellar plasma flows (including speed and density) are important methods of non-thermal atmospheric erosion, these factors could affect the evolution of a planet's environment and its potential habitability [5]. Here we focus on modelling the magnetic dipole moment of detected terrestrial exoplanets to determine their strength and consequent ability to protect their atmospheres from stellar effects.

## 2. Magnetism Model

Olson & Christiensen's [1] magnetic moment scaling law is currently the best available model and has been utilised in our calculations:

$$M = 4\pi r_0{}^3 \gamma \left(\frac{\bar{\rho}_0}{\mu_0}\right)^{1/2} (FD)^{1/3} \qquad (1)$$

where $M$ is the magnetic dipole moment (in $Am^2$), $\gamma$ is a fitting coefficient with a value of 0.1 – 0.2 deduced from numerical simulations [1], $\bar{\rho}_0$ is the bulk density of the fluid in the outer liquid core, which we have modelled based on Earth's density models ($\bar{\rho}_0 = 11\times10^6\ gm^{-3}$), $\mu_0$ is the magnetic permeability of the vacuum ($\mu_0 = 4\pi\times10^{-7} H/m$), and $D$ is the thickness of the outer liquid core rotating shell where convection occurs, modelled as $0.65r_o$ according to Heimpel et al. [6]. The planetary core radius parameter ($r_o$) was calculated using Zeng et al.'s semi-empirical relationship between core radius fraction, planetary radius, and mass for rocky planets [7][8]. The final factor in equation 1 is the average convective buoyancy flux, $F$, and we have used Lopez-Morales et al.'s equation to model this parameter [9]:

$$\frac{F}{F_\oplus} = \left(\frac{R_{O_l}}{R_{O_{l\oplus}}}\right)^2 \left(\frac{D}{D_\oplus}\right)^{2/3} \left(\frac{\Omega}{\Omega_\oplus}\right)^{7/3} \qquad (2)$$

where the local Rossby number ($R_{O_l}$= 0.1) gives $F_{max}$, which, in turn allows us to estimate the maximum dipolar magnetic moment. Since we do not have the planetary rotation rates (Ω) for all the currently detected terrestrial exoplanets, we examined the rotation periods of 70 solar system objects including planets, dwarf planets, their moons, Kuiper belt objects and main-belt asteroids to estimate an average rotation rate of $\sim 1.52 \pm 0.36\ \Omega_\oplus$. Additionally, Grieβmeier et al. was used to determine which exoplanets were tidally locked, as their orbital period will be equal to their rotation period [10]. These two rotation rate scenarios were used in calculations of equation 2.

## 3. Results

The maximum magnetic dipole moments of all confirmed terrestrial exoplanets were modelled and a clear trend between $M$ and $r_o$ was observed (Figure 1).

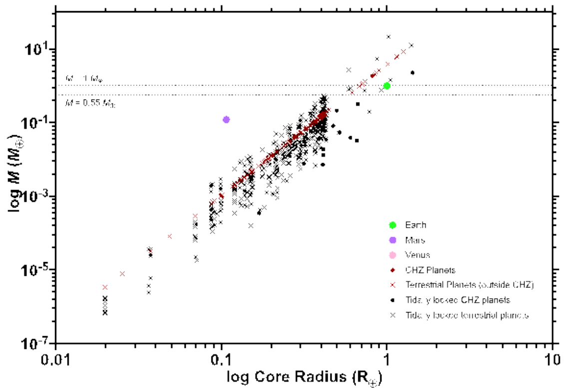


Figure 1: Maximum dipolar magnetic moments as a function of planetary core radius for both angular momentum scenarios: $1.52\Omega_\oplus$ (red), Tidally locked (black). Dotted lines signify magnetic moment threshold values.

It has been hypothesized that planets with a magnetic dipole moment of equal or greater strength than Earth's would have a magnetic field strong enough to protect the surface of the planet and preserve liquid water [9]. Therefore, we have set a threshold value of $1M_\oplus$ to determine which exoplanets could be classified as "magnetically habitable" i.e. protects surface water/life. Figure 1 shows that amongst our current sample, not all exoplanets possess a strong magnetic dipole moment. In spite of the fact that we modelled the best case scenario by calculating the maximum possible magnetic dipole moment, out of the 735 terrestrial planets in our model, only 21 of them had a magnetic moment equal to or larger than that of Earth's. However, would a lower magnetic moment value still adequately protect the surface of an exoplanet?

To answer this question, we once again looked to Earth, but instead of its current features, we examined the evolution of Earth's magnetic dipole moment. Based on models of mantle cooling from Tarduno et al., the paleointensity data suggests a virtual dipole moment of 3.8 (±0.4) x $10^{22}$ $Am^2$ for the NGB dacite ~3.45 Gya [11]. Since water and life were present on Earth at this time, we can reduce our lower limit on the magnetic dipole moment parameter from $\geq 1M_\oplus$ to $\geq 0.55M_\oplus$.

To determine the effect of planetary magnetism on terrestrial exoplanets in and near the circumstellar habitable zone (CHZ), we examined the maximum magnetic dipole moment values in the context of the optimistic and conservative habitable zones. Figure 2 showcases the probability of the CHZ exoplanets' magnetic moment being $\geq 0.55M_{\oplus}$. Probability values greater than 50% indicate a high likelihood that the planet has a magnetic moment strong enough to be classified as magnetically habitable; however, all exoplanets that have a non-zero probability of being $\geq 0.55M_{\oplus}$ are labelled as there is a chance that the planet has a magnetic moment strong enough to be protect the surface from stellar radiation.

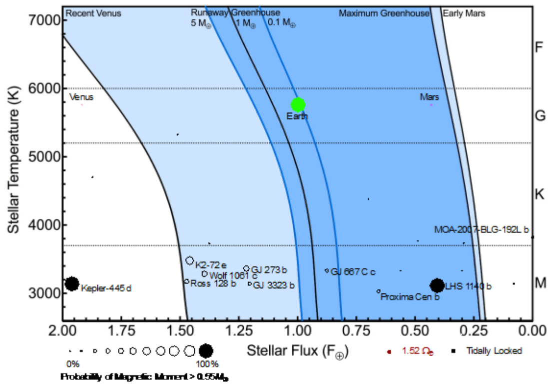


Figure 2: Sample of potentially habitable terrestrial planets and their location within the CHZ [8][9]. Size and opacity indicate the planets probability of having a magnetic moment strong enough to protect the surface of the planet from stellar effects. The planets that are labelled have a non-zero probability of having a magnetic moment $\geq 0.55M_{\oplus}$.

# 4. Summary and Conclusions

The results of the modelling and analysis revealed that a large number of planets currently defined as potentially habitable (rocky planets located in the CHZ), even with the best-case scenario of modelling the maximum possible dipole moment with the lowered threshold value, would not have a magnetic field strong enough to protect their surface, and any potential water or life on it, against stellar and cosmic irradiation. Based on our results of planetary magnetism and HZ boundaries, there are 4 exoplanets that consistently showed a significant magnetic protection: - K2-72 e, LHS 1140 b, GJ 273 b and Wolf 1061 c. Furthermore, Proxima Cen b, Trappist 1f and Trappist 1d show ~20% chance of having a strong enough magnetic field to protect their surfaces once the threshols is lowered, so there is a chance that they could be magnetically habitable.

Perhaps the most interesting outcome of Figure 2 is the effect that the magnetic moment value of Kepler-445 d could potentially have on definition of habitability. It could provide the opportunity to re-examine some of the "inhabitable" planets such as Kepler-445 d which, due to as yet unexplored circumstance, could potentially support liquid water in parts of their environment. If the habitable zone concept is based on the amount of incident stellar flux that reaches the surface of a planet so as to provide a planetary temperature suitable for liquid water, would it be possible that Kepler-445 d, which, despite being closer to its host star than the conventional HZ would allow, but due to having a magnetosphere 6 times as strong as Earth's, could be protected from the stellar rays and winds enough to provide a planetary surface environment suitable for liquid water?

While the models utilised here provide a broad overview of planetary magnetism, they do not account for changes of F and D with age, or for the effect of extreme external conditions, such as e.g. highly inhomogeneous heating or very strong stellar winds. More research on the star planet magnetic interactions needs to be done to determine how much effect the different stellar types and ages have on their planetary companions. Future research on this could more accurately inform the threshold limits for various stellar scenarios.

Our results showcase that introducing planetary magnetism as a parameter in habitability calculations in conjunction with the CHZ, limits the list of potentially life bearing exoplanets and provides more information on where we should begin our observational measurements. There are many more factors that we need to consider in order to further reduce the potential thousands of Earth-like planets to be discovered in the near-future using instruments such as TESS and CHEOPS. Examining the significance of planetary magnetism is the start of combining the current knowledge of astronomical and planetary features to narrow down our search for life and give our future observations the best possible starting point.

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