Boletim da Sociedade Astronômica Brasileira, **36**, no. 1, 208-211

Influence of magnetized winds from weak-lined T Tauris stars on the habitability of exoplanets

Y. Tamburus[1], N. F. S. Andrade[1], & V. Jatenco-Pereira[1]

[1] Instituto de Astronomia, Geofísica e Ciências Atmosféricas - IAG, Universidade de São Paulo
e-mail: ytamburus@usp.br
e-mail: natalia.fernanda.andrade@usp.br
e-mail: vera.jatenco@iag.usp.br

Abstract. Some models in the literature use the damping of Alfvén waves to accelerate the stellar wind of weak-lined T Tauri stars (WTTS). The current and growing search for rocky exoplanets with dimensions comparable to those of Earth makes it necessary to understand better the interaction between the stellar wind and the planetary magnetosphere since it can play a role as a shield, acting against the erosion of the atmosphere by the action of the wind. We aim to study the interaction of these magnetized winds with the magnetospheres of Earth-type planets in the habitable zones of their host stars and verify if their magnetospheres can preserve the planetary atmospheres. We assumed a simple constant damping mechanism for the Alfvén waves, and our preliminary results showed that some planets could sustain their atmospheres.

Resumo. Alguns modelos na literatura usam o amortecimento das ondas Alfvén para acelerar o vento estelar de estrelas T Tauri de linhas fracas (WTTS). A busca atual e crescente por exoplanetas rochosos com dimensões comparáveis às da Terra torna necessário entender melhor a interação entre o vento estelar e a magnetosfera planetária, uma vez que esta pode desempenhar um papel de escudo, atuando contra a erosão da atmosfera pela ação do vento. Nosso objetivo é estudar a interação desses ventos magnetizados com as magnetosferas de planetas do tipo Terra nas zonas habitáveis de suas estrelas hospedeiras e verificar se suas magnetosferas podem preservar as atmosferas planetárias. Supomos um mecanismo simples de amortecimento constante para as ondas Alfvén, e nossos resultados preliminares mostraram que alguns planetas podem sustentar suas atmosferas.

Keywords. Magnetohydrodynamics (MHD) – Planet-star interactions – Stars: winds – Stars: variables: T Tauri

1. Introduction

T Tauri stars are young, low-mass ($M_\star \leq 2M_\odot$) pre-main sequence stars, characterized by strong chromospheric activity, and emission lines such as H_α. In the evolved stages (< 10 Myr), the weak-emission T Tauri stars (WTTS) do not exhibit obvious signs of accretion or possess optically thick disks, suggesting they represent a later evolutionary stage where the circumstellar disk has either become optically thin or dispersed. They exhibit X-ray flares, likely from magnetic reconnection that heats the stellar plasma to very high temperatures (Güdel et al. 2007; Grankin 2017; Nicholson et al. 2018).

If there are oscillations in the magnetic field at the base of the wind, Alfvén waves will be generated. As they propagate outward, the dissipation of their energy and the transfer of their momentum to the plasma can heat and accelerate the wind (Vidotto & Jatenco-Pereira 2010).

The planetary magnetosphere is the region where the planet's magnetic field controls the movement of charged particles, i.e. it is located in the volume where the stellar wind is excluded by the planet's magnetic field. The boundary region between the wind and this field is called the magnetopause. On this surface flows a current that separates the two regions. Here the wind pressure and the magnetic pressure are in balance and this balance determines the extent of the magnetosphere The interaction of the stellar wind with the magnetosphere causes it to take on a circular shape in the daytime region (where the stellar wind is incident), because of the shock front it generates, and a cylindrical shape on the opposite side, where the magnetotail is located. The size of the magnetosphere depends not only on the radius of the planet and its magnetic field but also on the density of particles present in the stellar wind since it decreases with distance from the central object (Kivelson & Bagenal 2014)..

The current and growing search for rocky exoplanets with dimensions comparable to Earth's makes it necessary to better understand the interaction between the stellar wind and the planetary magnetosphere, since the latter can play the role of a shield, acting against the erosion of the planetary atmosphere by the action of the wind. See et al. (2014) performed numerical simulations to obtain the magnetospheres' dimensions of hypothetical Earth-type planets in the habitable zones of their host stars and compared them with the measurements of the Earth's magnetosphere in the Paleoarchean era (3,6 Gyr) for which the first evidence of life was registered and where the Earth's magnetic field is estimated to be half as strong as it is today.

2. Scientific goals

Using a sample from Güdel et al. (2007) of pre-main sequence stars, we built an MHD wind model for stars in the WTTS phase, analyzing the interaction between the magnetized wind driven by Alfvén waves and the planetary magnetosphere, including a constant damping mechanism in our analysis. We intend to investigate the consequent influence of the wind on the removal of the atmosphere and the consequences for the habitability of the planet.

3. Models

3.1. Wind velocity profile

We used the Jatenco-Pereira & Opher (1989) model, which considers a partially ionized flow, assuming a collimated jet. The wind structure used in this work is shown in Figure (1), where it presents divergent behavior of the magnetic field lines ($S > 2$) becoming radial ($S = 2$) after the distance r_T:

$$r_T = 10^{1/(S-2)} r_0. \quad (1)$$

Coronal holes are observed on the surface of the Sun, whose solid angle (Ω_0) varies by $7\Omega_0$ in the region between $r = R_\odot$ and $r = 3R_\odot$, where for $r > 3R_\odot$ the coronal hole becomes essentially radial and obeys the relation $F = \Omega/\Omega_0 = 7.26$ (Munro & Jackson 1977). Equation (2) uses an analytical expression to describe divergent geometry (Kuin & Hearn 1982),

$$A(r) = \begin{cases} A(r_0)\left(\frac{r}{r_0}\right)^S, & \text{if } r \leq r_T \\ A(r_0)\left(\frac{r_T}{r_0}\right)^S \left(\frac{r}{r_T}\right)^2, & \text{if } r > r_T \end{cases} \quad (2)$$

where $A(r)$ is the cross-section of the geometry used, at a distance r and r_0, and S is a parameter that determines the divergence of this geometry.

The fundamental equations that describe the Alfvén wave-guided wind model are based on the equations for the conservation of mass, momentum and energy, the latter being necessary when the behavior of temperature along the wind is unknown. Assuming that the wind is one-dimensional and that it propagates along the magnetic field lines, the continuity equation is:

$$\rho\, u A(r) = \text{cte}. \quad (3)$$

where **u** is the wind speed. Considering low amplitude Alfvénic fluctuations ($\delta B << B$) propagating at a low wavelength compared to the scale on which the physical properties of the wind vary, the equation of energy can be written as:

$$\frac{d\epsilon}{dr} = -\frac{\epsilon}{L} - \frac{\epsilon}{2}\frac{(1+3M)}{1+M}\left(\frac{1}{u}\frac{du}{dr} + \frac{Z}{r}\right), \quad (4)$$

where $M = u/V_A$ is the Alfvenic Mach number, V_A the Alfvén velocity, L the damping length, and Z is defined by:

$$Z = \begin{cases} S, & \text{if } r \leq r_T \\ 2, & \text{if } r > r_T. \end{cases} \quad (5)$$

Therefore, the equation describing the Alfvén wave-guided wind model is given by:

$$\frac{1}{u}\frac{du}{dr}\left[u^2 - c_s^2 - \frac{1}{4}\left(\frac{1+3M}{1+4M}\right)\left\langle\delta v^2\right\rangle\right] = \frac{Z}{r}\left[c_s^2 - \frac{GM_\star}{rZ} + \frac{1}{4}\left(\frac{1+3M}{1+M}\right)\left\langle\delta v^2\right\rangle + \frac{r}{2LZ}\left\langle\delta v^2\right\rangle\right], \quad (6)$$

where c_s is the speed of sound and $\left\langle\delta v^2\right\rangle$ is the mean square amplitude of the speed fluctuations.

3.2. Habitable Zone (HZ)

Kopparapu et al. (2013a) analyze the work of Kasting et al. (1993), which estimates the limits of habitable zones (HZ) of main sequence stars based on calculations of one-dimensional (1D) climate models. In general, habitability is the ability of Earth-like planets with $CO_2/H_2O/N$ atmospheres to have liquid water on their surfaces. Kasting et al. (1993) determined the internal limit of the ZH through water loss via photolysis and hydrogen escape. The outer boundary (called *maximum greenhouse* by Kopparapu et al. 2013a) is determined by forming CO_2 clouds, which lower the surface temperature by increasing the albedo.

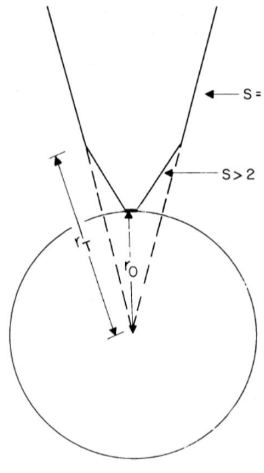

Figure 1. Geometry of the magnetic field (Jatenco-Pereira & Opher 1989).

The calculation for the distance from the HZ uses the effective stellar flux (S_{eff}), which is a constant used to maintain a given surface temperature. Thus, the S_{eff} parameter in Equation (7) is calculated from the climate model and is related to the type of star considered, and is obtained by a relationship between the stellar fluxes that reach the top of the atmosphere of a planet similar to Earth, and the effective temperatures applied. It is calculated as the ratio between the infrared flux ($F_{\rm IF}$) leaving the planet and the solar flux incident on the planet ($F_{\rm SOL}$), i.e. $S_{eff} = F_{\rm IF}/F_{\rm SOL}$. Therefore, we have (Kasting et al. 1993; Kopparapu et al. 2013a):

$$S_{eff} = S_{eff\odot} + aT_\star + bT_\star^2 + cT_\star^3 + dT_\star^4, \quad (7)$$

where $T_\star = T_{eff} - 5780$K, and the coefficients a, b, c and d correspond to values from the literature (Kopparapu et al. 2013b). In addition, the corresponding distance from the ZH can be calculated using Equation (8), given by the relation:

$$d = \left(\frac{L/L_\odot}{Seff}\right)^{0,5} \text{ UA}, \quad (8)$$

so that L and $L_\odot$ are the luminosities of the WTTS and the Sun, respectively.

3.3. Wind pressures

The chromospheric activity measured in Ca II H & K lines is given by (Mamajek & Hillenbrand 2008):

$$\log R_{\rm HK} = \frac{1}{3.46}\left[\log\left(\frac{L_{\rm X}}{L_{\rm bol}}\right) + 4.90\right] - 4.53. \quad (9)$$

It was considered that the WTTS wind has ram pressure (Equation 10; Cranmer & Saar 2011) and magnetic pressure (Equation 11):

$$P_{ram} = \frac{\dot{M}u_{\rm esc}}{4\pi r^2}, \quad (10)$$

$$P_B = \frac{B^2}{8\pi} = \frac{B_0^2}{8\pi}\left(\frac{r_0}{r_T^S}\right)^2\left(\frac{r_T}{d^2}\right)^2, \quad (11)$$

where $\dot{M} = 4\pi\rho_0 u_0 r_0^2$ is the mass loss rate, u_{esc} is the escape velocity, and B_0 is the initial magnetic field, adopted as 1 kG.

3.4. Magnetospheric dimension

The magnetosphere sizes of hypothetical Earth-type planets were calculated from the model by Grießmeier et al. (2004). An assessment of the T Tauri's wind pressure and the planet's magnetic pressure was carried out:

$$r_{MP} = \left[\frac{\mu_0 f_0^2 M_E^2}{8\pi^2 (P_{ram} + P_B)} \right]^{1/6}, \tag{12}$$

where μ_0 is the Earth's magnetic permeability, $f_0 = 1.16$ is a factor that considers the Earth's magnethosphere non-spherical shape and $M_E = 8\times10^{26}$ A cm^2 is the Earth's magnetic moment.

Tarduno et al. (2010) concluded that around 3.4 Gyr ago, the Earth had a geodynamo during the Paleoarchean period, which generated a magnetic field that was approximately 50% weaker than the current one, and managed to estimate a magnetosphere with a dimension of around $5R_E$, with $R_E = 6.371\times10^8$ cm being the radius of the Earth, when the Sun was 1.2 Gyr old. During this period, the Sun had a chromospheric activity of -4.6 according to the age-activity relationship (Mamajek & Hillenbrand 2008). So, considering that the Earth was able to sustain its atmosphere, it is reasonable to assume that a magnetosphere with dimensions equal to or greater than those of the Paleoarchean period would contribute to the defense of an Earth-like planet.

See et al. (2014), on the other hand, concluded that this level of chromospheric activity and terrestrial magnetic moment contributed to a terrestrial magnetosphere of approximately $7R_E$, according to Parker's model, during the Paleoarchean period. And so, a magnetospheric size range in the Paleoarchean period would possibly be given by 5-$7R_E$. Therefore, the level of chromospheric activity was important in determining whether a magnetosphere larger than Earth's in this period could be sustained.

4. Results

Figure (2) shows the wind velocity profile for one of the sample stars, obtained by integrating the equation using the 4-order Runge-Kutta method (RK-4). It also shows the locations of the transition radius (blue dashed line) and the habitable zone of this star (green dot-dash line). In this case, this velocity profile has divergence $S = 3.5$ and terminal velocity $u_\infty = 319.4$ km/s, which is an expected value, since its coronal temperature was adopted as being $T = 2.1 \times 10^5$ K (Preusse et al. 2005).

Figure (3) shows a simulation between the pressure balance of the stellar wind (ram and magnetic) and the planets (magnetospheric) located in the HZs. The coloring of the graphs was done according to the chromospheric activity from Equation (9). Furthermore, the present-day (orange dot-dash line) and the Paleoarchean (green box) magnetospheric sizes are shown, where Tarduno et al. (2010) say it is reasonable to assume that during this period, it would already be able to contribute to the planet's defense.

A coronal temperature of $T = 2.1 \times 10^6$ K was adopted for stars with a mass greater than 0.8 $M_\odot$, for the others we used $T = 2.1 \times 10^5$ K, because in order to integrate Equation (6) it is necessary that initially both sides of this equation are < 0 so that the wind increases its velocity, and then both sides become > 0 and it stabilizes. The variables that influence this behavior are: S, L, u_0, and T.

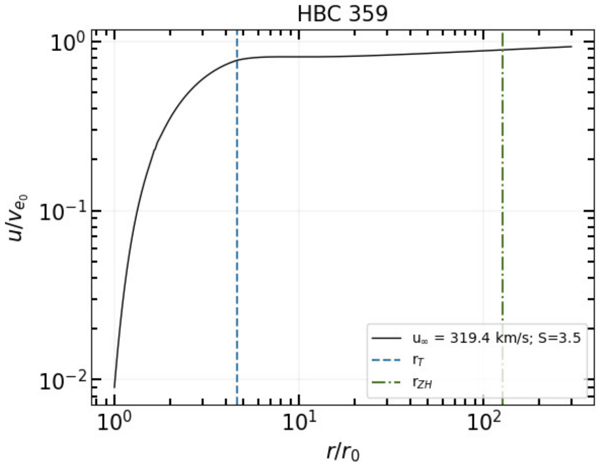

Figure 2. Velocity profile of WTTS star HBC 359.

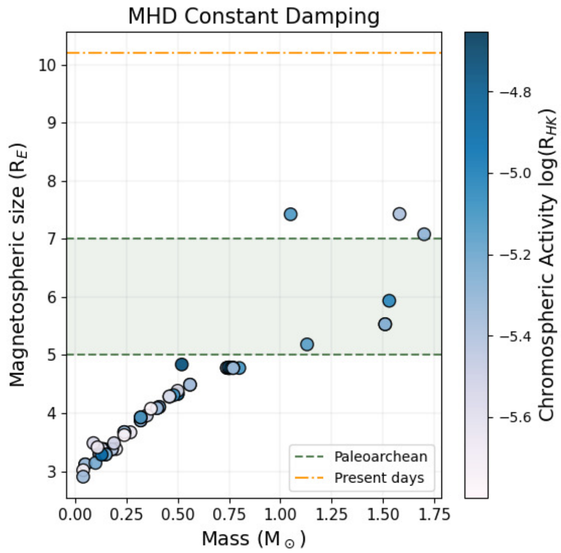

Figure 3. Simulation for the relationship between the size of the magnetosphere of Earth-type planets in habitable zones of T Tauri stars as a function of their masses, for the MHD wind. It also shows the density of chromospheric activity, as well as the size range of the Earth's magnetosphere in the Paleoarchean period and that of the present day.

We can see that some stars have magnetospheric values greater than 5 R_E, which is the Paleoarchean limit. Therefore, these stars are candidates for being able to sustain their atmospheres and thus be habitable.

Figure (4) shows what the magnetospheric sizes would be if magnetic pressure were disregarded, and as expected, their dimensions increase significantly and they also lose the linear behavior caused by the magnetic field. However, this calculation is not correct, as the magnetic field in this type of star is significant and cannot be disregarded.

We noticed that the magnetospheres seem to have a linear relationship with the mass of the host star, and this is probably because the calculation of the location of the habitable zone depends on the stellar mass. Another observation is that the magnetic pressure (Equation 11) has the greatest influence among the ram pressure in this calculation (Equations 10), and is also

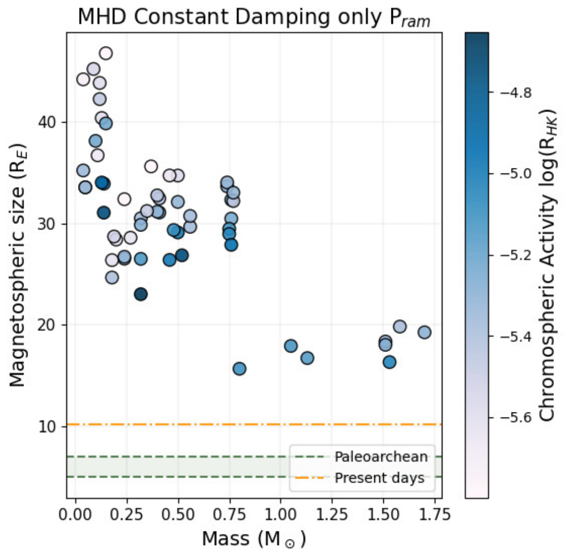

Figure 4. Size of the planetary magnetosphere in relation to the mass of its host star using constant damping and disregarding magnetic pressure.

responsible for the linear behavior in Figure (3), as the magnetic field decreases radially.

5. Conclusions

We notice that magnetic wind pressure significantly influences the size of magnetospheres because, in Figure (3), only some planets can sustain their atmospheres. However, in Figure (4), when magnetic pressure is disregarded, almost all planets have magnetospheres greater to the Paleoarchean size, which it is not an expected behaviour in the universe.

Acknowledgements

I would like to thank Proex (Capes) for the financial support under process number 88887.820782/2023-00.

References

Cranmer, S. R., & Saar, S. H. 2011, ApJ, 741, 54.
Grankin K., T. 2017, Astronomical Society of the Pacific Conference Series, vol. 510, p. 90.
Grießmeier, J. M., et al. 2004, A&A, 425, 753.
Güdel et al. 2007, AAS, 39, 753.
Jatenco-Pereira, V., & Opher, R. 1989, MNRAS, 236, 1.
Kasting, J. F., Whitmire, D. P., & Reynolds, R. T. 1993, Icar, 101, 108.
Kivelson, M., & Bagenal, F. 2014, *Encyclopedia of the Solar System* 1st Ed., eBook ISBN: 9780080573137, cap. 28, Planetary Magnetospheres.
Kopparapu, R. K., et al. 2013a, ApJ, 765, 131.
Kopparapu, R. K., et al. 2013b, ApJ, 770, 82.
Kuin, N. P. & Hearn, A. G., 1982. A&A, 114, 303.
Mamajek, E. E., & Hillenbrand, L. A. 2008, ApJ, 687, 1264.
Munro, R. M. & Jackson, B. V., 1977. ApJ, 213, 874.
Nicholson B. A., et al. 2018, MNRAS, 480, 1754.
Preusse, S., Kopp, A., Buchner, J., & Motschmann, U. 2005, A&A, 434, 1191.
See et al. 2014, A&A, 570, A99.
Tarduno, J. A., et al. 2010, Science, 327, 1238.
Vidotto A., & Jatenco-Pereira V. 2010, Advances in Space Research, 46, 509.