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Rotation–magnetic activity relation in low-mass stars

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Abstract. Magnetic fields are observed in most low-mass stars (M<2M$_\odot$) in the pre-main sequence and main sequence phases. In this work, we investigate the rotation–magnetic activity relation using models generated by the stellar evolution code ATON and observational data from the literature. Convective turnover times and Rossby numbers (Ro) were determined theoretically for a sample of 847 stars. We analyze the data in the rotation–magnetic activity diagram (L_X/L_{bol} *vs* Ro) and fit them with a two-part power-law function. The values of Ro calculated with our theoretical convective turnover times are systematically smaller than those calculated with semi-empirical convective turnover times. Nevertheless, our fit parameters are consistent with others in the literature.

Resumo. Campos magnéticos são observados na maioria das estrelas de baixa massa (M<2M$_\odot$) na pré-sequência principal e sequência principal. Neste trabalho, investigamos a relação rotação-atividade magnética usando modelos gerados pelo código de evolução estelar ATON e dados observacionais disponíveis na literatura. Os tempos convectivos e os números de Rossby (Ro) foram determinados teoricamente para uma amostra de 847 estrelas. Analisamos os dados no diagrama rotação–atividade magnética (L_X/L_{bol} *vs* Ro) e os ajustamos com uma função de lei de potência em duas partes. Os valores de Ro calculados com os nossos tempos convectivos teóricos são sistematicamente menores quando comparados com aqueles calculados com tempos convectivos determinados semi-empiricamente. Apesar disso, os nossos parametros de ajustes são consistentes com os encontrados na literatura.

Keywords. stars: activity – stars: low-mass – stars: rotation

1. Introduction

Investigating magnetic activity is important because it help us understand the evolution of stars and evaluate the potential habitability of planetary systems. One way to study magnetic activity is to investigate the relation between some of its indicators (such as $H\alpha$, CaII and X-ray emission) and rotation. This investigation was initially made with the rotation period, but magnetic activity is better correlated with the Rossby number, Ro (the ratio between the rotation period and the convective turnover time, τ_c). τ_c can be obtained semi-empirically or through stellar evolution models.

By organizing the $\log(L_X/L_{bol})$ data as a function of log(Ro), we get a characteristic plot (Fig. 1), that presents two distinct regions separated by a threshold value of the Rossby number, named saturated Rossby number (according to the literature, $Ro_{sat} \sim 0.1$). In the unsaturated region ($Ro > Ro_{sat}$), magnetic activity increases as the Rossby number decreases. In the saturated region ($Ro \leq Ro_{sat}$), the magnetic activity does not depend on the Rossby number, showing a constant value around $L_X/L_{bol} \sim 10^{-3}$.

Until recently it was believed that completely convective stars were exclusively found in the saturated region, while stars with radiative interiors were found in both regions. The presence of completely convective stars in the unsaturated region, first revealed by Wright & Drake (2016), is of great interest to understand magnetic activity in low-mass stars.

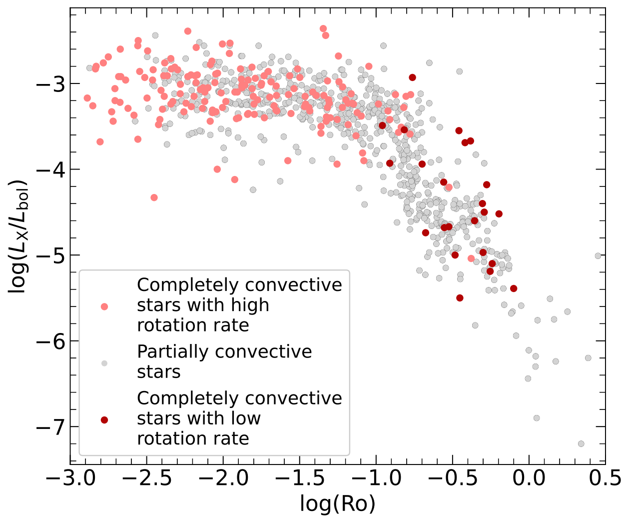

Figure 1. $\log(L_X/L_{bol})$ x log(Ro). Data taken from Wright et al. (2011) and Wright et al. (2018).

2. Models

The evolutionary tracks used in this work were generated by the stellar evolution code ATON, considering the solar chemistry described by Asplund et al. (2009), differential rotation and initial angular momentum given by Kawaler (1987), $J_{Kaw} = 1.566 \times 10^{50} (M/M_\odot)^{0.985}$ g cm^2 s^{-1}. Convection was treated using the traditional Mixing Length Theory (Böhm-Vitense 1958) with the convection efficiency $\alpha = 2.0$ and the surface boundary conditions were obtained by non-gray atmosphere models by Allard, Hauschildt & Schweitzer (2000). The adjustment between the interior and the atmosphere was made at optical depth $\tau = 3$.

3. Mass, age and convective turnover time determinations

In order to determine masses and ages of the stars from Wright et al. (2011), we used the effective temperatures and luminosities published by them, except for those stars to which they assigned a null luminosity and those whose positions in the HR diagram fell below our tracks. For these stars, which are very low-mass, we recalculated their luminosities using the bolometric corrections from Pecaut & Mamajek (2013) in the V band as a function of V-K. For the stars from Wright et al. (2018), we used the (V - K) – effective temperature relations from Pecaut & Mamajek (2013), and luminosities were obtained using the bolometric corrections from Mann et al. (2015, 2016) in the K band as a function of V - J. In this process, we used the extinction laws from Rieke & Lebofsky (1985).

With bolometric luminosities and effective temperatures in our hands, we put the stars from our sample in a theoretical Hertzsprung-Russell (HR) diagram ($L/L_\odot \times T_{\rm eff}$). The stars' masses and ages were obtained through an interpolation method, where the position of each star in the HR diagram was compared with the evolutionary tracks generated by the `ATON` code, Landin et al. (2022) in the mass range from 0.085 $M_\odot$ to 1.9 $M_\odot$.

The local convective turnover time is defined as the ratio between the mixing length (ℓ) and the convective velocity (v_c). The mixing length is the characteristic convective length scale where a mass element moves before dissolving in the surrounding environment. The convective turnover time for each star of our sample was obtained by double interpolation (in mass and age) in the τ_c values from the evolutionary tracks generated by the `ATON` code.

4. Fitting Methods

Using our theoretical convective turnover times and observed rotation periods from Wright et al. (2011, 2018), we calculated the Rossby number for each star and we built a rotation–magnetic activity diagram ($L_X/L_{\rm bol} \times {\rm Ro}$). We fit the data with a two-part power-law function:

$$\frac{\rm L_X}{\rm L_{bol}} = \begin{cases} {\rm CRo}^{\beta}, & \text{if Ro} > {\rm Ro_{sat}}, \\ \left(\frac{\rm L_X}{\rm L_{bol}}\right)_{\rm sat}, & \text{if Ro} \leq {\rm Ro_{sat}}, \end{cases} \tag{1}$$

where $(L_X/L_{\rm bol})_{\rm sat}$ is the mean saturation level of the fractional X-ray luminosity, β is the power-law slope for unsaturated stars and C is a constant. The fitting parameters where obtained with two different methods. The first one, named method I, is based on dividing our data in 34 Ro intervals and analysing amplitude, variance, standard deviation and mean values of $\log(L_X/L_{\rm bol})$ for each interval. Aiming to estimate the saturated Rossby number, we looked for log(Ro) values for which the mean of $\log(L_X/L_{\rm bol})$ deviated most significantly from ~ -3. We also looked for which values of log(Ro) occurred a considerable increase in the variance and in the amplitude because of the contribution of objects from the unsaturated region. The fit parameters obtained with method I are shown in the top left panel of Fig. 2. The second method, named method II, focuses on identifying the ${\rm Ro_{sat}}$ value that minimizes the standard deviation with respect to Eq. 1. For ${\rm Ro} > {\rm Ro_{sat}}$, we fitted the data using the linear regression method on the log-log scale, keeping the linear coefficient fixed, so that for ${\rm Ro} = {\rm Ro_{sat}}$, $L_X/L_{\rm bol} = (L_X/L_{\rm bol})_{\rm sat}$.

Utilizing the second method, we searched for the ${\rm Ro_{sat}}$ that minimized the data standard deviation with respect to Eq. 1, obtaining $\log({\rm Ro_{sat}}) = -1.28 \pm 0.07$. This value coincides with the one that minimizes the difference between $\log(L_X/L_{\rm bol})_{\rm sat}$ and $\log(L_X/L_{\rm bol})$ at $\log({\rm Ro_{sat}})$ obtained by linear regression. For this value of ${\rm Ro_{sat}}$, we obtained $\beta = -1.72 \pm 0.02$ and

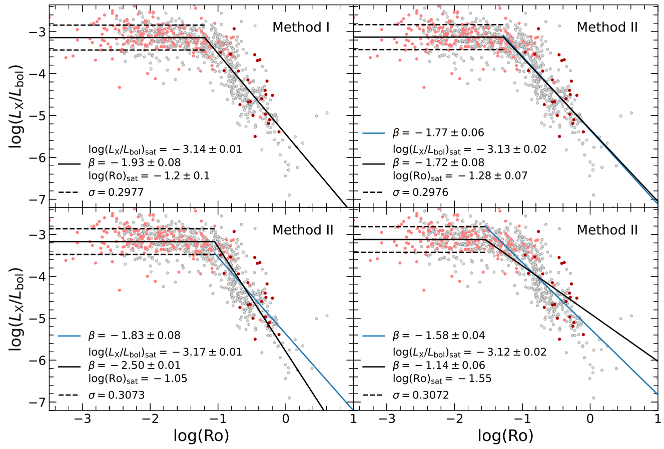

Figure 2. $\log(L_X/L_{\rm bol})$ x log(Ro) plot with the fits obtained with method I and II. Solid black lines are the result of the data fit with Eq. 1. Blue lines show the default linear regression fits. The bottom dotted lines are the equivalent to $\log(L_X/L_{\rm bol})_{\rm sat} - \sigma$, and the top dotted lines refer to $\log(L_X/L_{\rm bol})_{\rm sat} + \sigma$.

$\log(L_X/L_{\rm bol})_{\rm sat} = -3.13 \pm 0.02$. This fit is shown in the top right panel of Fig. 2.

Blue fits for $\log({\rm Ro_{sat}}) = -1.55$ (bottom right panel of Fig. 2) and $\log({\rm Ro_{sat}}) = -1.05$ (bottom left panel of Fig. 2) were made using linear regression processes without restrictions for the linear coefficient. These two values were selected so that at $\log({\rm Ro}) = \log({\rm Ro_{sat}})$, $\log(L_X/L_{\rm bol})$ equals $\log(L_X/L_{\rm bol})_{\rm sat} + \sigma$ and $\log(L_X/L_{\rm bol})_{\rm sat} - \sigma$, respectively (where σ is the standard deviation).

5. Conclusions

With the convective turnover times calculated with the `ATON` code, we were able to reproduce the rotation–magnetic activity diagram, although our Ro values are systematically smaller than those of Wright et al. (2011, 2018). The fits obtained with our two methods are consistent with each other and with others in the literature. In addition, with the τ_c calculated theoretically, we were able to reproduce the positions of completely convective stars found in the unsaturated region of the rotation–magnetic activity relation. In the future, we intend to extend our analysis to others samples, including stars from clusters with different ages.

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