Proceedings of 12th Cambridge Workshop on Cool Stars, Stellar Systems, & The Sun, 2003 University of Colorado.

Activity-rotation Relationship: Interpretation of an X-ray Derived Rossby Number

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Abstract. In this work we present results of a new study on the relationship between X-ray emission and an empirical Rossby number. Using an extended sample of 238 dwarfs in the $B-V$ range 0.5 – 1.6, including 102 field stars and 136 members of clusters, we have first established power-law correlation functions between the X-ray to bolometric luminosity ratio and the rotation period for stars in 7 selected color ranges. We have then determined a color-dependent function, $\tau_e(B-V)$, which allows us to derive a single "optimized" relation between $L_{\rm x}/L_{\rm bol}$ and an empirical X-ray-derived Rossby number $R_{\rm o}^{emp} = P_{\rm rot}/\tau_e$.

We show that τ_e scales with $B-V$ as $L_{\rm bol}^{-0.5}$ and for $B-V > 1.3$ it is significantly lower than the theoretical convective turnover time. Our result demonstrates that for non-saturated coronae the $L_{\rm x}$ – $P_{\rm rot}$ relation is equivalent to the $L_{\rm x}/L_{\rm bol}$ vs. $R_{\rm o}^{emp}$ relation.

1. Introduction

The Rossby number parameter $R_{\rm o} = P_{\rm rot}/\tau_{\rm conv}$, related to the dynamo number by the inverse proportionality law $N_{\rm D} \propto R_{\rm o}^{-2}$, is usually used as a good indicator of the efficiency of the dynamo mechanism in the generation and amplification of the stellar magnetic field and consequently of the stellar magnetic activity. While the rotation period $P_{\rm rot}$ can be directly measured, $\tau_{\rm conv}$ is usually empirically determined assuming an activity-Rossby number relationship (Noyes et al. 1984, Stepien 1994) or derived from theoretical models. The aim of this work is to explore whether the use of an X-ray empirically-determined Rossby number effectively improves our physical understanding of the correlation between X-ray emission and rotation.

In this work: (i) We determine an empirical X-ray-derived $\tau_{\rm e}$ as a function of the $B-V$ color; (ii) we use this function ($\tau_{\rm e}$) to evaluate an empirical Rossby number $R_{\rm o}^{emp}$ for a sample of field dwarfs and cluster members observed by ROSAT and for which periods measurements are available; (iii) we compare the X-ray emission vs. $P_{\rm rot}$ relationship with the analogous relationship between X-ray emission and $R_{\rm o}^{emp}$; (iv) we show that $\tau_{\rm e}$ is significantly lower than the

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theoretical convective turnover time for $B-V>1.3$ and scales with $B-V$ as $L_{\rm bol}^{-0.5}$.

2. Sample Selection and Properties

We have selected 238 dwarfs, including 102 field stars and 136 stars belonging to Pleiades, Hyades, IC 2602 and α Persei open clusters, with available rotational periods and observed by ROSAT-PSPC. The sample, including stars in the color range $0.51 < B-V <1.61$ and covering the period range $0.4 \leq P_{rot} \leq 48$ days, represents a significative extension of the original sample selected by Stepien (1994) for his study on the applicability of the Rossby number to late-type dwarfs (including dM stars).

Rotation periods are derived from photometric measurements (see the reference list for details) except for 16 M-type field stars in Delfosse et al. (1998), for which the periods are calculated from $v \sin i$ data and accurate radius determinations (Beuermann et al. 1999).

X-ray luminosities and X-ray to bolometric luminosity ratios are retrieved from the original papers for all cluster stars and for 74 of the 102 field stars, or evaluated from ROSAT count rates (from HEASARC) for the remaining 28 field stars, using a constant count rate-to-flux conversion factor of $6 \cdot 10^{-12}$ erg cm^{-2} cnt^{-1} (see Hempelmann et al. 1995).

3. X-ray Emission Level vs. Stellar Rotation Period

We have explored the relationships $L_{\rm x}$ vs. $P_{\rm rot}$ and $L_{\rm x}/L_{\rm bol}$ vs. $P_{\rm rot}$ separately in 7 color-selected subsamples. Essentially in all cases two distinct correlation regimes exist: at low rotation rates the emission level (either $L_{\rm x}$ or $L_{\rm x}/L_{\rm bol}$) increases as a power-law function of the rotation period, with an exponent consistently equal to -2, within statistical errors for any subsample; at high rotation rates the emission reaches a saturation level $L_{\rm x}/L_{\rm bol} \approx 10^{-3}$, with no dependence on $P_{\rm rot}$.

The period at which saturation occurs ($P_{\rm rot}^{sat}$) and the saturation X-ray emission level have been determined, for each color range, as free parameters of the piece-wise power-law functions with fixed exponents.

In Fig. 1 we have reported all the color-selected data points and the related fits in the same plot: in the non-saturated regime the relation between $\rm L_x$ and $\rm P_{rot}$ (left panel) is very similar for all color bins (same slope and intercept), while the saturation is reached at decreasing rotation periods and decreasing X-ray luminosity levels for increasing $B-V$ color. Note the complementary behavior of the $L_{\rm x}/L_{\rm bol}$ vs. $P_{\rm rot}$ case (Fig. 1, right panel): the saturation occurs approximately at the same level of $L_{\rm x}/L_{\rm bol}$ for all of the spectral classes, but the color-dependence of $P_{\rm rot}^{sat}$ induces a spread in the $L_{\rm x}/L_{\rm bol}$ power-laws describing non-saturated stars.

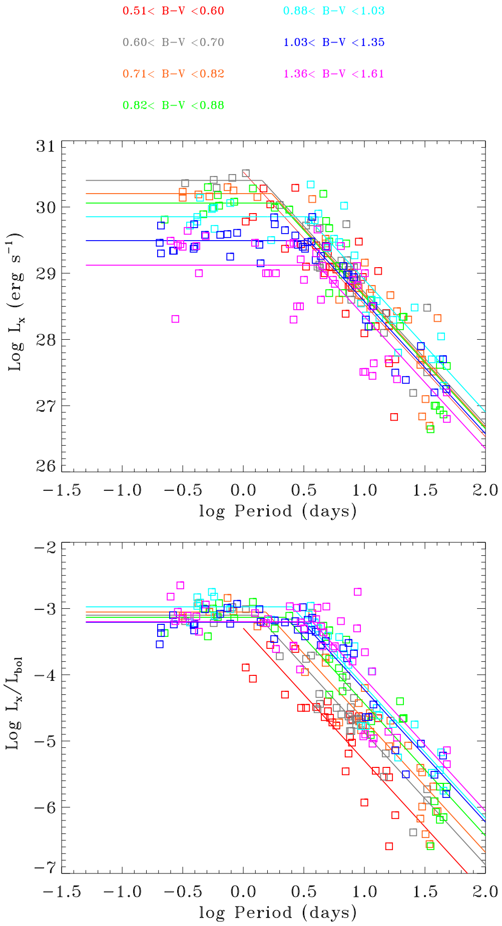

Figure 1. Upper panel: X-ray luminosity vs. rotation period for the stars in all the color ranges. Solid lines are derived from the fitting procedure described in the text. Lower panel: X-ray to bolometric luminosity ratio vs. rotation period for all the stars in our sample.

4. Empirical Determination of the Rossby Number

We have first considered the family of power laws:

$$L_{\rm x}/L_{\rm bol} = A_k P_{\rm rot}^{-2} \tag{1}$$

which describe the behavior of the non-saturated stars in Fig. 1, with A_k dependent on the $B-V$ color range considered.

A single relationship for all the stars can be obtained by scaling:

$$P_{\rm rot} \Rightarrow \frac{P_{\rm rot}}{\tau_{\rm e}(B-V)} \tag{2}$$

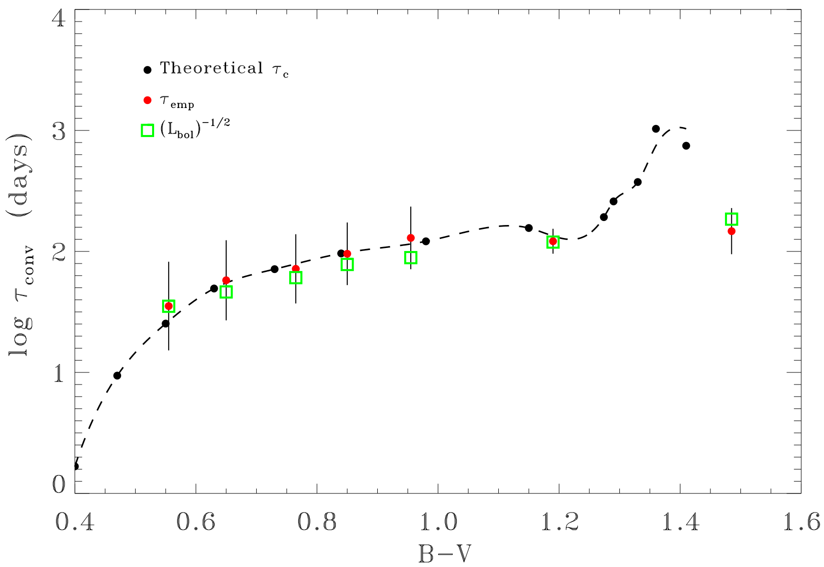

Figure 2. Comparison between empirically-determined τ_e (red dots) and theoretical models (black dots with dashed line); green squares mark the $L_{bol}^{-1/2}$ behavior.

where the color-dependent function $\tau_e(B-V)$ can be obtained as $(A_k/C)^{1/2}$, with $C = constant$, so that

$$L_x/L_{bol} = C\left(\frac{P_{rot}}{\tau_e}\right)^{-2} \tag{3}$$

The new variable P_{rot}/τ_e can be dubbed "X-ray empirical Rossby number", but τ_e should not be confused with the stellar convective turnover time, τ_c. In fact, by comparison with the theoretical τ_c derived from detailed stellar models (Ventura et al. 1998), we find that the empirically X-ray-derived function τ_e follows the theoretically computed convective turnover time for stars in the $B-V$ range 0.5 – 1.2, while for later type stars τ_e shows a flatter trend with respect to τ_c (Fig. 2).

5. What is the Physical Meaning of the Empirical Rossby Number?

We have demonstrated that a single power-law provides a good color-independent description of the L_x vs. P_{rot} relationship, for non-saturated stars. Does the L_x/L_{bol} vs. R_o^{emp} relationship represent a real improvement?

The scaling:

$$L_x \Rightarrow \frac{L_x}{L_{bol}} \tag{4}$$

introduces a color-dependent vertical shift of the power-law (Fig. 1, lower panel), which can be compensated by an horizontal shift provided by the scaling:

$$P_{\rm rot} \Rightarrow \frac{P_{\rm rot}}{L_{\rm bol}^{-1/2}} \qquad (5)$$

In fact we show in Fig. 2 that the empirically-determined color function $\tau_{\rm e}(B-V)$ is equivalent to $L_{\rm bol}^{-1/2}$, except for a constant scaling factor.

The above results, together with the deviation of $\tau_{\rm e}(B-V)$ from the theoretical turnover time, suggest that for stars in the non-saturated regime the two relationships $L_{\mathbf{x}}$ vs. $P_{\mathbf{rot}}$ and $L_{\rm x}/L_{\rm bol}$ vs. $R_{\mathbf{o}}^{emp}$ are equivalent.

6. Results and Conclusions

Based on the examined correlations between X-ray emission and stellar rotation period, we have found that:

(1) The empirically X-ray-derived function $\tau_{\rm e}$ is very similar to the theoretically computed convective turnover time for stars in the $B-V$ range $0.5-1.2$, while for later type stars $\tau_{\rm e}$ is significantly different.

(2) $\tau_{\rm e}(B-V)$ is essentially the same as $L_{\rm bol}^{-1/2}$, for the entire $B-V$ color range.

(3) For non-saturated stars the $L_{\rm x}$ vs. $P_{\rm rot}^{-2}$ relationship is equivalent to the $L_{\rm x}/L_{\rm bol} \propto (P_{\rm rot}/\tau_{\rm e})^{-2}$, hence there is no strong empirical reason to prefer one description to the other, furthermore because of point (1) there is no physical reason to prefer the $L_{\rm x}/L_{\rm bol}$ vs. $R_{\rm o}^{emp}$ relationship.

(4) Because of point (1) and (2) above the empirical Rossby number cannot be trivially interpreted as a proxy of the efficiency of the stellar magnetic dynamo.

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