THE CORONAL ROTATION-ACTIVITY RELATIONS IN LATE-TYPE STARS

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ABSTRACT

I discuss EINSTEIN X-ray observations of late-type (G and K) stars. For the RS CVn systems and the evolved G stars, there is a linear relation between X-ray surface flux and stellar angular velocity. The situation is more complex among the G-K dwarfs: rapid rotators, with rotational periods less than $\sim 10^d$, also show a linear relation between X-ray surface flux and angular velocity, but the slow rotators fall some two orders of magnitude below that relation.

I. INTRODUCTION

It has been evident for some time that rapid rotation in late-type stars influences the heating of their chromospheres and coronae. Kraft (1967) showed that F-G dwarfs with strong chromospheric Ca II H and K emission lines had larger $\langle V \sin i \rangle$ than did those stars without detectable emission. Skumanich (1972) proposed, based on data for the Pleiades, Hyades, and the Sun, that the Ca II emission flux decreased as the stellar age $T^{-1/2}$, as did $\langle V \sin i \rangle$. Hence, the chromospheric emission flux scaled linearly with stellar rotational velocity.

By observing the relationship between velocity (either rotational or angular) and an appropriate measure of the activity (a measure of the non-radiative heating rate), one might hope to gain insight into the processes which drive the activity in these convective stars. These processes likely involve the stellar dynamo, given the correspondence of regions of high activity with regions of emerging magnetic flux on the Sun (Vaiana and Rosner 1978). Such studies may improve our understanding of convective dynamos and how they interact with the stellar atmosphere. In this work I have obtained EINSTEIN X-ray observations of a number of late-type stars with known rotation periods, in order to investigate the coronal rotation-activity relation.

II. THE OBSERVED ROTATION-ACTIVITY RELATIONS

I use the ratio of the X-ray to the bolometric flux L_x/L_{bol} as the measure of stellar coronal activity. The justification is that L_x/L_{bol} is a measure of the fraction of the stellar energy balance radiated from the corona and should scale with the energy in the closed magnetic flux

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tubes. In addition, L_x/L_{bol} is convenient in that it is proportional to the X-ray surface flux for stars of the same T_{eff}. As a rotational parameter I prefer the stellar angular velocity Ω, which is the inverse of the stellar rotation period P, and is not subject to uncertainties due to the stellar inclination.

A. K Stars

The first and largest sample of stars is the RS CVn systems (Hall 1976), which are close binaries showing extreme activity levels (Walter and Bowyer 1981). Rotation periods are the photometric periods, or in their absence synchronism is assumed. The bolometric flux is that of the active star in the system. In Figure 1, I plot L_x/L_{bol} vs. $P(=1/\Omega)$. There is a clear trend in the data, with activity increasing with more rapid rotation. The best fit power law relation is $L_x/L_{bol} \propto \Omega^{1.17\pm0.12}$, which is a linear relation within the errors.

There is no significant correlation between L_x/L_{bol} and V since the rotational velocities of the slow rotators, which are giants, are not significantly different from those of the shorter period systems. Among these stars, there is no dependence of L_x/L_{bol} upon the surface gravity (Walter and Bowyer 1981).

This linear relation is not unique to the RS CVn systems: active K dwarfs, T Tauri stars, and weak emission line PMS stars (Walter and Kuhi 1981; Mundt et al. 1982) all fall on this relation. Caillaut (1982) has found the same for BY Dra stars. In fact, among rapidly rotating G8-K5 stars, only the Algol systems (White 1982) fall significantly below the relation (although the secondary of Algol does fit). The data indicate that this linear relation is universal for K stars, both single and binary, as long as significant mass transfer is not occurring. This may not be surprising, if the dynamo is sensitive primarily to the depth of the convective zone and the stellar angular velocity.

B. G Stars

The second sample of stars I studied includes 16 F8-G5 dwarfs. The best least-squares power law fit is significantly steeper than the linear relation found for the K stars, with a slope of 2.5 (Walter 1982), and is consistent with the steep relation obtained by Pallavicini et al. (1981). However, the fit is poor and the residuals show a systematic trend: the data seem to require a shallower slope among the rapid rotators, and a steeper slope at long periods. Figure 2 shows the fit to only those stars with $P < 12^d$. This fit has a slope of 1.25 ± 0.21, which is identical to the linear K star fit.

The justification of cutting the data at this point lies in the observations of Vaughan (1980) and Vaughan and Preston (1980), who found among G dwarfs a bifurcation in chromospheric activity levels, with the active stars showing stochastic long-term chromospheric variability and the inactive stars showing cyclic variability. At G0, the location of the gap corresponds to an age of $\sim 10^9$ yrs. By Skumanich's (1972) relation between V_{rot} and age, this also corresponds to a rotation period of $\sim 12^d$. Hence the active, rapid rotators which show a linear relation between L_x/L_{bol} and Ω correspond to the chromospherically active, young stars. Slow rotators, like the Sun, fall some two orders of magnitude below the extrapolation of the linear relation. It is not clear if the slope of the relation changes, or if the linear relation is scaled down by two orders of magnitude.

I find these X-ray data, taken together with the chromospheric observations, to be convincing evidence of a change in the nature of the dynamo at a given rotation period in dwarfs. This may be due to a juxtaposition of many dynamo modes in the rapid rotators, with only the fundamental mode excited at low Ω (Durney et al. 1981), or to a change in the pattern of convection at a critical Ω. I note that there is marginal evidence, based on five K dwarfs, that there is a similar break in the L_x/L_{bol} vs. Ω relation for K dwarfs (Walter 1982).

Finally, a small sample of five G giants is consistent with the linear portion of the relation found for the G dwarfs, in that the scaling, within the errors, is identical for $P < 12^d$. However, for the giants as for the long-period RS CVns, the linear relation extends to periods of ~100 days without evidence of any break. While this is clear evidence of a difference between giants and dwarfs, it is not clear what the physical basis for the difference is.

C. F Stars

The last sample of stars includes 12 F3-F5 dwarfs with measured V sin i. These stars are interesting in that they have small convective zones, and may not have the same type of dynamo mechanism as later type dwarfs. The analysis is still in a preliminary state, but there is no

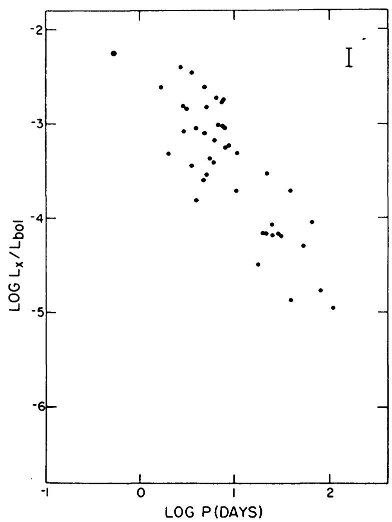

Fig. 1. The coronal rotation-activity relation for G8-K2 stars. Most of the stars are RS CVn systems, but some single K dwarfs are included. The relation is nearly linear, with $L_x/L_{bol} \propto \Omega^{1.2\pm0.2}$ ($\Omega = P^{-1}$).

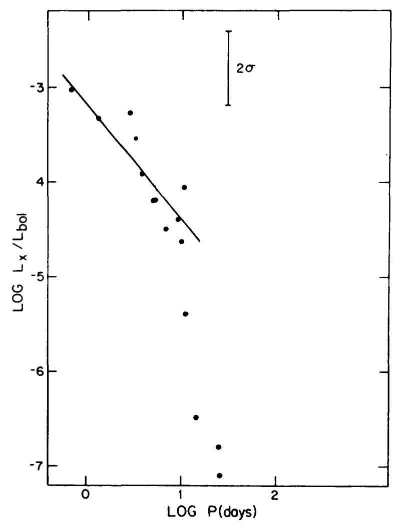

Fig. 2. The coronal rotation-activity relation for F8-G5 dwarfs. The line is the best fit relation for $P \lesssim 12^d$; it has a slope identical to that found for the K stars. The slow rotators including the Sun fall well below this relation.

indication for any correlation of L_x/L_{bol} with V sin i; all stars show similar L_x/L_{bol}, although V sin i varies from 50 km s^{-1} to <6 km s^{-1}. L_x/L_{bol} for these stars is $\sim 10^{-5}$, which is two orders of magnitude brighter than Pallavicini et al. (1981) found for the O, B, and A stars. These early F stars seem to behave neither like the A or G stars.

III. SUMMARY

There is no single coronal rotation-activity relation. G-K dwarfs with rotation periods between $\sim 12^h$ and 12^d, and G-K giants and subgiants exhibit a linear relation between L_x/L_{bol} and Ω. Slowly rotating G-K dwarfs have L_x/L_{bol} some two orders of magnitude lower than an extrapolation of the linear relation. The break in the relation occurs at the same rotation period as the chromospheric break observed by Vaughan (1980).

The W UMa systems appear to show a turnover in the relation, with $L_x/L_{bol} \propto \Omega^{-3}$ (Rucinski and Vilhu 1982). These stars are not only more rapidly rotating than the detached systems, but may have disturbed circulation patterns in the convective zones, because the stars are in contact.

Converting L_x/L_{bol} to surface fluxes by removing the T^4 term in L_{bol} shows that at a given P, the K stars show about twice the X-ray surface flux as the G stars. Swank et al. (1981) have shown that K RS CVn systems have a hot ($T \gtrsim 3 \times 10^7$ K) coronal component contributing half the X-ray flux, whereas earlier type RS CVn systems show a weak, if any, hot component (cf. Walter et al. 1982). It may be that the deeper convective zone of the K stars is fundamental to the existence of this hot coronal component.

The data show that the two stellar parameters which strongly affect the activity levels are Ω and the spectral type. Surface gravity is not important. Stellar duplicity appears important only in enforcing rapid rotation. Among the rapid rotators, the relation between Ω and coronal activity is linear.

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DISCUSSION

ZWAAN: Let me take issue with your statement that stellar chromospheres may be heated by acoustic waves. If you mean to say *purely* acoustic, without any role of magnetic fields, then your statement is wrong, since you could not explain the large range in chromospheric surface fluxes from stars of similar T_{eff} and g.

WALTER: I agree. There is clear evidence as you, among others, have shown, that the chromospheric Ca II flux is magnetically influenced. However, as Basri et al. show (following paper), at least in the RS CVn systems the chromospheric flux does not vary with Ω. The situation is complex, but may be less so in the corona, where the X-ray emitting coronal gas must be magnetically confined, and does show strong scaling with Ω.

SODERBLOM: I would like you to comment on the spread in the L_x/L_{bol} vs. P (rotation period) diagram for RS CVn's. There is nearly an order-of-magnitude spread in L_x/L_{bol}. Given this, couldn't one line fit the G-dwarf data adequately (although I grant the two-line fit is clearly better)?

WALTER: The scatter about the best fit relation for the RS CVn stars is about a factor of 3 (Walter and Bowyer: 1981, *Astrophys. J.* **245**, p. 671). This is similar to the range of solar coronal variability, and may well indicate that the scatter is due to intrinsic stellar variability. For lack of a better estimate, I adopted this variance for the G dwarfs. Even with such large error bars, the single power law fit is not good ($\chi^2 \approx 1.3$; cf. Walter: 1982, *Astrophys. J.* **253**, p. 753), and a second power law significantly improves the fit. The quadratic trend in the residuals to the single power law fit is suspicious, and the similarity of the unit slope in the rapidly rotating G dwarfs to that of the RS CVn systems is unlikely to be coincidental.

GIAMPAPA: (1) What is the physical justification for using L_x/L_{bol} as opposed to L_x ? (2) How would your correlations change if you used L_x ? (3) If you use the L_x/L_{bol} parameter, you might find an increase in this ratio as you go towards the late M dwarf stars. However, I find a decline in chromospheric activity towards the very late M dwarf stars. Thus the L_x/L_{bol} parameter and observed Hα emission, or lack thereof, would contradict each other. Would you like to comment on this?

WALTER: (1) L_x/L_{bol} is a measure of the fraction of the total stellar energy balance which gets into the corona. It may be related to the energy field up in the stellar magnetic field. Additionally, for stars of a given spectral type, L_x/L_{bol} is proportional to a surface flux. This facilitates comparing stars of different radii. L_x is OK if the sample is, for example, the G dwarfs, but I hesitate to compare giants and dwarfs using L_x. (2) For the RS CVn systems, L_x is essentially independent of P (period), since L_{bol} scales with P (see answer to Rosner's question below). For the dwarfs there will be absolutely no changes. (3) I do not know what L_x does in late M dwarfs. It may well decline, in which case L_x/L_{bol} would decline, and there would be no contradiction.

ROSNER: If, as you stated, comparison of L_x vs. P (period) gives no correlation, but comparison of L_x/L_{bol} vs. P does, doesn't that mean that L_{bol} is correlated with P ?

WALTER: Yes. RS CVn stars are evolved, detached binaries. As such, there is a rough correlation between the radius of the active, evolved star and the semi-major axis of the system. All are of roughly solar mass, so L_{bol} does correlate with P. This was first shown by Young and Koniges (1977, *Astrophys. J.* **211**, p. 836), who found that M_V increased as $P^{10/3}$ in long-period RS CVn systems.Because of these variations of stellar radius, it is very important to normalize the X-ray flux. L_x/L_{bol} is a surface flux for stars of the same spectral type, since $L_{bol} \sim R^2T^4$. Hence in the RS CVn stars, L_x/L_{bol} ($\sim F_x$) $\sim \Omega \sim P^{-1}$.

VAIANA: Your points for RS CVn's are basically scattered around two regions, the rapid rotators and the slow rotators. You have assumed that the slow rotators are corotating. If you exclude them, can you see any dependence at all?

WALTER: Yes. Of course the slope is much more poorly determined because the range in P is only an order of magnitude, but it is consistent with unity (cf. Walter and Bowyer: 1981, *Astrophys. J.* **245**, p. 671). There is no physical justification for subdividing the RS CVn systems into subgroups, except for taxonomic purposes (i.e., differentiating the RS CVn ***systems*** as defined by Hall, with $1^d < P < 14^d$, from those stars exhibiting the RS CVn *phenomenon*; cf. comment by D. Popper in *IAU Symp.* **88**). As concerns synchronous rotation in the slow rotators, many are observed to rotate synchronously. λ And does not, but 7 of the remaining 14 have observed photometric waves, and are in synchronous rotation. The assumption of corotation in the other seven should be quite valid.

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