A NON-EMPIRICAL ROTATION-ACTIVITY RELATION FOR RS CVn BINARIES USING RADIO LUMINOSITIES

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ABSTRACT. An analysis of a comprehensive survey of radio luminosities for RS CVn binary systems is given. A comparison is made between the rotation-activity correlations found using the usual semi-empirical Rossby number and a Rossby number deduced from detailed convection zone models. The use of a non-empirically derived Rossby number does not significantly improve the rotation-activity correlation. Although there are some indications that the rotation-activity correlations are marginally better for theoretically derived convective parameters this study is limited by the size of the sample.

1. INTRODUCTION

The correlation between rotation and chromospheric activity in late-type stars first suggested by Kraft (1967) is now beyond question. These stars generate magnetic fields by a dynamo mechanism, the efficiency of which depends partly on the forces produced by rotation and partly on those produced by convection. In particular, the depth of the convection zone, or its convective turnover timescale, is thought to play a role in the field generation. Since stellar activity seen in many wavebands is directly influenced by the presence of emerging magnetic flux it is not surprising that stars of later spectral type (that is with deeper convection relative to their radius) will show stronger dynamo behaviour than stars of earlier spectral type, for a given rotation period. The resulting rotation-activity correlation is visible in many wavelength regions. For single stars relations between coronal emissions and rotation have been reported by Pallavicini *et al.* (1981) and Schrijver, Mewe & Walter (1984). Chromospheric relations were also found by Middelkoop (1981) and Noyes *et al.* (1984). X-ray observations (Vaiana *et al.* 1981; Walter 1981) have also demonstrated the link between stellar activity, rotation rate and spectral type.

In binary stars the levels of activity are generally seen to be higher than in similar single stars. One such class of objects is the RS CVn binaries (Hall 1976) normally consisting of at least one component of spectral type F-G V-IV and which show the Ca II H & K lines in emission outside of eclipse. Features such as strong coronal X-ray and radio emission, variable Hα emission, strong UV chromospheric and transition region line emission and frequent flaring activity are typical of these objects and are classical indicators of magnetic activity. The components of RS CVn systems are at least partially evolved. Popper & Ulrich (1977) concluded that emission characteristics develop as they enter the Hertzsprung gap. More recently both Barrado *et al.* (1994) and Gunn, Mitrou & Doyle (1997) confirmed the evolved status of RS CVn components. In this part of the HR diagram hydrogen shells can ignite in the stellar interior and envelope expansion can occur. Hence the convection zone properties can be significantly altered from main-sequence stars. Metallicity is also important because the temperature of stars at the base of the giant branch is very sensitive to this parameter. Since RS CVn binaries are tidally locked their spin periods are quite high which leads to increased levels of activity relative to single stars of the same age.

Many authors have studied the correlation of RS CVn flux measurements with rotational parameters; namely the rotational period or rotational surface velocity. The dynamo theory of activity production suggests that correlations should be more readily apparent using a parameter which involves the convective properties of the star and its interaction with the magnetic field. Drake, Simon & Linsky (1989) analysed a comprehensive survey of radio flux measurements for a large sample of chromospherically active binaries. These data were originally discussed in terms of simple rotational parameters and not a convection-related parameter. Expanding on this analysis, Gunn (1996) used empirically derived values of the Rossby number which includes a term for convection effects and found a marginal improvement in the rotation-activity correlations using these radio luminosities. More recently Gunn, Mitrou & Doyle (1997) derived a set of non-empirical Rossby numbers for a large sample of RS CVn binaries and discussed the correlations using the flux observed by the International Ultraviolet Explorer (IUE) in the CIV line at 1550Å. They found only another marginal improvement over the empirical values and concluded that additional factors may be at work in the manifestation of magnetic activity in RS CVns.

In this paper we return to the radio flux measurements of Drake, Simon & Linsky (1989) and analyse whether the use of the non-empirical values of Rossby number derived by Gunn, Doyle & Mitrou (1997) give any improvement in the rotation-activity correlation.

2. THE ROSSBY NUMBER

An appropriate quantity used to characterise the efficiency of the magnetic dynamo that gives rise to stellar activity is the Rossby number, $R_o = P_{rot}/\tau_{conv}$, where P_{rot} is the stellar rotation period and τ_{conv} is the characteristic convective turnover timescale. For studies of tidally synchronised binaries such as the RS CVns it is usual to equate the orbital and rotation periods, i.e. $P_{orb} = P_{rot}$. Since τ_{conv} is a function of spectral type, R_o characterises the level of dynamo activity for stars of differ-

Table 1. Results of the regression and correlation analysis for the sample of stars from the Drake, Simon & Linsky (1989) survey using the empirical values of Rossby number ($R_o(E)$) from Noyes *et al.* (1984) and the non-empirical values of Rossby number ($R_o(NE)$) from Gunn, Mitrou & Doyle (1997). The table shows the independent and dependent variables used in each analysis, the number of stars in the sample n, the subset of data used ('a' for all, 'g' for giants, 's' for subgiants and 'd' for dwarfs), the maximum likelihood (ML) regression line gradient a and the product moment correlation coefficient r.

X	Y	n	subset	a	r
$\log L_6$	$\log P_{orb}$	56	a	+0.187	+0.267
		20	g	-1.614	-0.480
		20	s	-0.252	-0.085
		16	d	-0.973	-0.521
$\log L_6/L_{bol}$	$\log P_{orb}$	56	a	-0.677	-0.468
		20	g	-1.689	-0.514
		20	s	-0.649	-0.220
		16	d	-0.938	-0.488
$\log L_6$	$\log R_o(E)$	56	a	+0.053	+0.196
		20	g	-1.574	-0.463
		20	s	-0.222	-0.108
		16	d	-0.961	-0.485
$\log L_6/L_{bol}$	$\log R_o(E)$	56	a	-0.866	-0.515
		20	g	-1.655	-0.513
		20	s	-0.699	-0.279
		16	d	-1.048	-0.588
$\log L_6$	$\log R_o(NE)$	56	a	-0.442	+0.026
		20	g	-1.476	-0.446
		20	s	-0.909	-0.323
		16	d	-1.202	-0.522
$\log L_6/L_{bol}$	$\log R_o(NE)$	56	a	-1.135	-0.611
		20	g	-1.494	-0.547
		20	s	-1.204	-0.383
		16	d	-1.139	-0.514

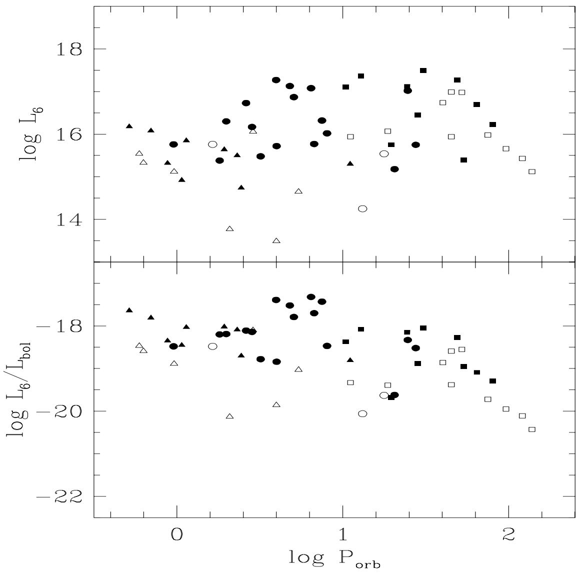

Fig. 1. Plot of $\log L_6$ and $\log L_6/L_{bol}$ against $\log P_{orb}$ for the sample of stars from the Drake, Simon & Linsky (1989) survey. Symbols are circles for giants, squares for subgiants and triangles for dwarfs. Those points which are upper limits are plotted as open symbols.

ent rotation periods and is expected to decrease with increasing activity. Observationally this assertion has been demonstrated by Noyes (1983) who found that Ca II emission strength, when normalised to bolometric flux, was related to the product of angular rotation rate and an additional function of spectral type. That function was identified with the convective turnover timescale.

To form an estimate of R_o for a given star it is necessary to calculate the convective turnover timescale τ_{conv}. Such modelling has been performed by Gilman (1980), Gilliland (1985), Rucinski & Vandenberg (1986) and Kim & Demarque (1996). The usual method involves modelling the stellar convection zone using standard mixing length theory and stellar structure codes. Noyes *et al.* (1984) used convective turnover timescales computed from an empirical fit to the models of Gilman (1980). Although Gilman's work involved models for various stellar masses Noyes *et al.* (1984) used a standard mass-colour relationship to find a mean relation between τ_{conv} and the (B-V) colour index. The problem with this approach is that the models from which the empirical fits are derived apply only to main-sequence stars. For studies of active binary systems, in which one or both components may be evolved, the empirical relationships derived by Noyes *et al.* (1984) and others (most notably Gilliland 1985 and Stępień 1989) may not be appropriate. However, a consistent set of theoretically derived τ_{conv} values could be used to study rotation-activity correlations in evolved active binaries. Gunn, Mitrou & Doyle (1997) derived such a set of non-empirical values and compared the correlations obtained using these to those obtained using the non-empirical relationship of Noyes *et al.* (1984). They found only a marginal improvement in correlations and suggested that some additional factor other than rotation and convection may be influencing the activity levels. For their study they used the flux observed in the CIV 1550Å line. In this study we combine the results of Gunn (1996) and Gunn, Mitrou & Doyle (1997) by using the radio luminosities as activity indicator and the Rossby number as dynamo indicator. For details of the derivation of Rossby numbers for this study the reader is referred to Gunn, Mitrou & Doyle (1997). Briefly, a modified version of the stellar evolution code of Eggleton (1971, 1972, 1973) and Han, Podsiadlowski & Eggleton (1994) was used with updated nuclear reaction rates, neutrino losses and opacities.

3. DATA ANALYSIS

The Drake, Simon & Linsky (1989) survey consists of radio flux measurements at 6 cm for a sample of 122 RS CVn and related binary systems with widely varying orbital periods. Gunn (1996) analysed the radio luminosities of a subset of 108 of these systems to find only a marginal improvement of correlation between rotation period and empirical Rossby number. In the present study only those stellar components which are common to this analysis and that of Gunn, Mitrou & Doyle (1997) are used. This results in only 56 stars from the original sample so in order to compare the results of empirical and

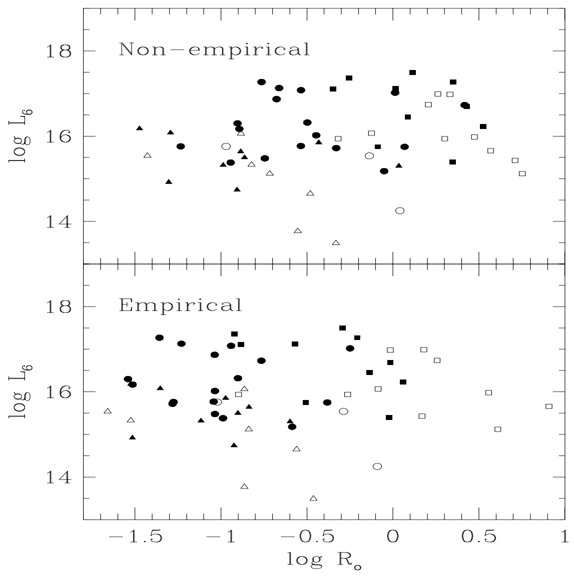

Fig. 2. Plot of $\log L_6$ against both empirical and non-empirical $\log R_o$ for the sample of stars from the Drake, Simon & Linsky (1989) survey. Symbols are as in Figure 1.

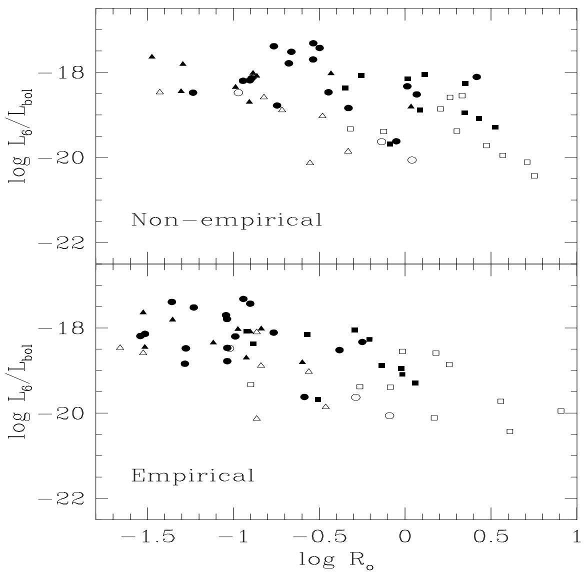

Fig. 3. Plot of $\log L_6/L_{bol}$ against both empirical and non-empirical $\log R_o$ for the sample of stars from the Drake, Simon & Linsky (1989) survey. Symbols are as in Figure 1.

non-empirical Rossby numbers the analysis of Gunn (1996) was repeated with the smaller sample.

Many of the data points in the sample represent only an upper limit to the radio emission. Such detections should not be ignored because they provide information about the possible emission from a given system but should not, in contrast, be allowed to bias the sample. However, the analysis of such censored data can be achieved using an iterative maximum likelihood (ML) linear regression procedure known as the expectation maximization (EM) algorithm. Essentially the ML analysis does a linear least-squares fit to the data and includes a statistically correct treatment of the censored points. The basic technique is discussed by Miller (1981) and its application to astronomical data has been presented by Feigelson & Nelson (1985) and Isobe, Feigelson & Nelson (1986).

If very weak relations exist between parameters (in that the gradient of the linear relation is small) the data can still be highly correlated. For the conclusions of regression analysis to be valid a measurement of goodness of fit is also required. In the Drake, Simon & Linsky (1989) survey they conclude that two parameters show no significant correlation simply when the gradient of the regression line is small. Since these regressions were for log-log relationships the gradient is a measure of the power of the dependent variable in the regression relationship and therefore reveals nothing about how well the data are correlated. The usual product moment correlation coefficient r is a sufficient measure for censored data since the effect of censoring on this parameter is small. A zero gradient naturally implies that data are completely uncorrelated. The correlation coefficient measures the dispersion of the data around the regression line so r cannot uniquely declare the correspondence between two parameters. For these reasons an improvement in a correlation can be defined as an increase in *both* the modulus of the ML gradient and r. A reversal of sign of either parameter is regarded as no significant improvement. The ML analysis was applied to the sample of 56 RS CVn stars and separately to the subsets of dwarfs, subgiants and giants. The analysis was done between orbital period P_{orb}, empirical Rossby number $R_o(E)$ and non-empirical Rossby number $R_o(NE)$ and for 6-cm radio luminosity L_6 and normalised radio luminosity L_6/L_{bol}.

4. RESULTS AND DISCUSSION

Table 1 shows the results of the regression and correlation analyses on the data using orbital periods and both empirical and non-empirical Rossby numbers. This table lists the parameters used, the number of stars in the sample, the subset of the data used (a, g, s or d), the ML linear regression line gradient a and the product moment correlation coefficient r. Figure 1 shows a plot of the radio luminosity L_6 and normalised radio luminosity L_6/L_{bol} against orbital period for this sample taken from the Drake *et al.* (1989) survey. Symbols indicate the luminosity class of the stars and whether the luminosities are upper limits. Figure 2 shows the radio luminosities L_6 against the empirical Rossby numbers derived using the (B-V) magnitude and the Noyes *et al.* (1984) relationship and the non-empirical values derived for these stars by Gunn, Mitrou & Doyle (1997). Figure 3 shows the radio luminosities normalized to the bolometric luminosities (L_6/L_{bol}) against both the empirical and non-empirical Rossby numbers.

From the regression and correlation results there appears to be a weaker inverse correlation between radio luminosity and Rossby number or rotation period for subgiant stars than for other luminosity classes. Gunn (1996) found this to be the case for dwarf stars in the analysis of the larger sample. However, the correlations do improve steadily from period to empirical R_o to non-empirical R_o for both radio luminosity L_6 and normalised radio luminosity L_6/L_{bol}. The lack of significant correlation for subgiants may be due to the small number in the sample (20). However, for these subgiants a much greater gradient is found in the regression analysis using the non-empirical R_o for both L_6 and L_6/L_{bol}. This may suggest that indeed the non-empirical values are an improvement. For dwarfs and giants no apparent change or a small decrease in the correlation coefficients are found going from orbital period to empirical R_o to non-empirical R_o for both L_6 and L_6/L_{bol} although for dwarfs the gradient increases. The correlation of L_{bol} alone with Rossby number has not been studied. In general the highest degrees of correlation and the greatest regression gradients are found using non-empirical Rossby numbers and the normalised radio luminosity. These results may be expected on the basis of the dynamo theory of stellar activity but the small variations in correlation for these data and the small sample sizes means that their interpretation must be cautious. As found by Gunn (1996) the luminosity class is a significant factor in the determination of activity levels or at least its dependence on convection. This analysis has concerned a single activity indictor which relates to the large scale coronal activity of the binary systems. The lack of significant correlations like those found for lower atmospheric activity indicators may mean other factors such as surface gravity or binarity may be operating which mask the underlying rotation-activity relation.

5. CONCLUSIONS

It has been demonstrated that the use of a non-empirically derived Rossby number does not significantly improve the rotation-activity correlation for radio luminosity measurements of RS CVn binaries over that found using the orbital period or empirical Rossby number. There are some indications that the rotation-activity correlations are marginally better for theoretically derived convective parameters, though this study is limited by the size of the sample. Alternatively these results may be interpreted in a similar manner to those of Gunn, Mitrou & Doyle (1997) in which it was suggested that current dynamo theory is limited in its application to the study of active binary stars because of the uncertainty in the angular velocity-depth profile in stellar interiors and the unknown effects of binarity and surface gravity.

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