PERIOD-ACTIVITY RELATIONS IN CLOSE BINARY SYSTEMS

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Since the advent of extensive ultraviolet observations of cool stars, it has been clear that the stellar activity observed is not directly correlated with the star's position on the HR diagram (Basri and Linsky 1979, Stencel et al. 1980). Observations of an important chromospheric diagnostic, the MgII resonance lines, led to the conclusion that stellar chromospheric activity had only a weak dependence on spectral type, and exhibited large variations within a given spectral type. Because of the strong observed correlation of solar activity with magnetic fields, the field is thought to be a natural candidate for the extra parameter which predicts the level of activity. Unfortunately, it is quite difficult to measure magnetic fields directly in most cool stars. Another method with which to examine correlations between magnetic field and stellar activity indirectly is the hypothesis that magnetic fluxes are directly related to a combination of the convective and rotational parameters of a star through its generation in a magnetic dynamo. The α-ω dynamo theory (Parker, 1979) predicts a direct correlation between differential rotational velocities and field generated. Durney and Robinson (1982) predict basically a linear dependence of the emergent flux on the angular velocity of the star. One might therefore expect that in stars with the same fundamental stellar parameters, the amount of activity observed would depend on the rotational velocities. This is difficult to test because most cool stars are slow rotators and only a few rotational velocities are known.

We have undertaken to study this question by looking at close binary systems which present a number of advantages over the single stars: (1) well known rotation periods covering two orders of magnitude, (2) generally strong (easily detected) activity, (3) well known evolutionary status and stellar parameters, (4) an extensive existing survey of their coronal activity. We have used orbital rather than rotational period; these are known to be equivalent for most of the stars (where a different rotation period is known we have used it) but the assumption probably breaks down for the longest period systems. The X-ray survey of RS CVn stars by Walter and Bowyer (1981) had already

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shown a linear period-activity relation. We have observed both RS CVn and less evolved close binary systems; we separate the K subgiant RS CVn stars for special consideration as a very homogeneous group of active stars. We have chosen to present the results to reflect surface fluxes vs. angular velocity. The alternative method of Pallavicini et al. (1982) (total flux vs. v sin i) was less appealing both because it retains errors in the stellar distance and radius (and the ambiguity of sin i) and because we feel our parameters are more fundamental to the question posed. We therefore plot ratios of fluxes against period. The ratio of a diagnostic flux to ℓ_{bol} (at the earth) gives us a measure of surface activity to total emergent flux; we have also examined the diagnostics relative to the emergent chromospheric flux (as measured in MgII). Our errors in ℓ_{bol} are limited to the bolometric corrections to m_V (small) and corrections for inactive components in some of the systems.

Our aim was to survey as many of the stars observed in X-rays as we could with the IUE satellite. As there was a known period-activity correlation in their coronae, we could learn how the relation behaves as one moves down through the transition region into the chromosphere. We have used the same diagnostics, measurement techniques and calibrations as in other IUE surveys (Ayres, Marstad, and Linsky, 1981; Hartmann, Dupree, and Raymond, 1981). We estimated the calibration and measurement errors each to be 15%. Of more concern was the intrinsic stellar variability, which could easily cause the stars to change their mean activity levels by a factor of two, and leads to at least the same level of scatter in any relations found. A linear least-squares fit to the points in the log (flux ratio) vs. log (P) plane provides power law relations between activity and period which we give as the slopes of the fitted lines. We excluded a few stars from the analysis: ER Vul because its period is too short for this class of stars and 33 Psc and o Dra because their coronal fluxes were anomalously low.

We first discuss the set of X-ray/ℓ_{bol} vs. P relations. For the full sample we find a slope of −0.9 which is basically the same as the Walter and Bowyer (1981) result; the K subgiant subsample yields almost the same slope (−0.8). All of the slopes and χ^2 are listed in Table 1. Note that χ^2 for the full sample is not particularly good; it is almost always larger than for the restricted sample because the spectral inhomogeneity of the full sample shows up as a real disparity between classes in the relation. In particular, the main sequence G star binaries lie systematically lower than the K subgiants for the same rotational periods. Thus relations which include a variety of spectral classes cannot be used directly to deduce correlations between magnetic field and activity without correction for this effect. We observe this same effect for almost all the diagnostics. The MgII observations give a very different period-activity relation than X-rays: a very small slope with almost no correlation between chromospheric activity and period. There is a division by decreasing activity levels into K subgiants, G subgiants, and G dwarfs--each exhibiting the same flat slope and covering similar ranges in period. The scatter for each class is rather small but the entire sample again shows larger scatter and slope. We note that ℓ_{bol} itself exhibits a slope with period of about 1.1 for the K subsample and .5 (but with a great scatter) for the full sample (this has been explained by Young and Koniges 1977, whose work originally inspired this study). This fact does not reflect on our relations, however, which are between surface flux and period. In looking at the full sample for the other diagnostics, we see three basic groupings. Those showing flat (0 to -0.2) slopes are MgII, OI, NV, HeII and SiIV. Intermediate slopes (-0.35 to -0.6) are seen in CI, SiII, CII, CIV, and X-rays show a large slope. A number of these relations have rather larger χ^2, but we believe there is a better way to look at the data.

Because stellar activity is not determined primarily by spectral type (except on average, as found above) and because MgII seems to exhibit little correlation with period, we have re-examined the relations using MgII flux rather than ℓ_{bol} as our normalizer. This has the effect of looking at magnetic field effects which are above the general level of chromospheric activity, rather than the total energy flux (which could be poorly related to activity). The effect of doing this is rather striking; all of the relations show less scatter and smaller χ^2, and the distinction between the various subclasses (and even the excluded stars) is largely eliminated. This effect cannot be due to errors in ℓ_{bol} (which are rather small and randomly distributed). It reflects the fact that stellar activity at all temperatures is correlated. One likely explanation is that the energy flux which heats the chromosphere has the same basic source as for higher layers, although the heating mechanisms could be different. This source is not directly correlated with photospheric flux. Our relations, especially for the K subgiants now have formal errors in slope of ±.05 at the 95% confidence level. The diagnostics are grouped in the following fashion: MgII, OI and NV are basically flat (0. to -0.2), the CI at -0.2, SiII, CII at -0.3 (SiIV shows anomalously large scatter), HeII and CIV at -0.4, and X-rays at -0.7. AR Lac always lies anomalously low. The behavior of NV is quite surprising as it is closest in temperature to X-rays, but we have no reason to distrust the data, despite the fact that it is a fairly weak line sometimes disturbed by the wing of Lyman-α at IUE resolution. The scatter is quite reasonable, and a separate analysis of the correlations among the diagnostics turns up nothing unusual.

The relations are of sufficient quality to warrant a number of conclusions. First, the activity in the RS CVn systems is not elevated purely because they are rapid rotators. The behavior of our sample suggests that activity increases with later spectral type and with evolution off the main sequence. These both could be explained by the increasing role of convection. Second, the chromosphere exhibits at best a small reaction to the increase in rotation velocity. The transition region diagnostics are somewhat more sensitive, but coronal fluxes are the most sensitive measure of magnetic activity. We note that this increasing sensitivity is rather consistent with the correlation between the diagnostics in these stars (Basri and Laurent, 1982); if MgII increases with a slope of .15 and X-rays increase relative to MgII with a slope of 4.5 (as they found) then we would get our observed results. This is true for most of the diagnostics. What isn't clear is whether those relations are largely due to the increasing effect of the magnetic field, or to a small increase of activity with field in the chromosphere which is amplified in the higher layers by some non-magnetic agency (like stability criteria). Adopting the former viewpoint, we find that the directly magnetic contribution to chromospheric activity (assuming $B \propto P$) is << 10%, in the transition regions it is ~ 10%, and in the corona ~ 70-90%. There are several lines of evidence that there is a major component of chromospheric heating which is much less sensitive to the magnetic flux directly.

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Table 1: Period-Activity Relations

		Slope	χ^2	[<σ>~.5(.2)]		Slope	χ^2
MgII	14[1] K	-.1[2]	.1	CII	13 K	-.4(-.3)	.5(.3)
	33 All	-.25	.4		27 All	-.6(-.4)	.7(.2)
OI	13 K	-.0[2] (-.0)[3]	.3(.2)	CIV	14 K	-.5(-.4)	.4(.2)
	15 All	-.2(-.0)	.6(.2)		24 All	-.4(-.35)	1.0(.25)
CI	11 K	-.35(-.2)	.4(.2)	SiIV	11 K	-.3(-.3)	.9(.6)
	23 All	-.55(-.3)	1.3(.3)		19 All	-.15(-2.)	.8(.5)
SiII	12 K	-.4(-.3)	.4(.3)	NV	12 K	-.0(-.1)	.6(.2)
	15 All	-.35(-.3)	.4(.3)		21 All	-.0(-.0)	.7(.25)
HeII	12 K	-.4(-.4)	.4(.2)	X-ray	18 K	-.8(-.7)	.6(.35)
	21 All	-.2(-.2)	1.2(.4)		32 All	-.9(-.65)	1.6(.6)

[1] number of stars used
[2] slope of the relation log (line/ℓ_{bol}) vs. log Period (days)
[3] slope of the relation log (line/MgII) vs. log Period

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DISCUSSION

VILHU: Do you have any idea on the basis of your observational material how single stars may be different from binary stars at the same spectral type and rotational period, i.e., what are the effects of binarity?

BASRI: We see some increase in activity for our binaries compared to single stars rotating at the same rate. As we report elsewhere, we also see steeper correlations between the diagnostics compared with the single stars of Ayres, Marstad, and Linsky. It may well be that binarity is an added complication to understanding the amount of activity observed.

WALTER: I disagree with your statement that binaries and single stars show different activity levels. In my X-ray samples, there are *no* obvious differences between close binaries and single stars with the same rotation periods.

BASRI: My statement was meant to refer to the ultraviolet diagnostics, for which the binaries seem to be slightly more active.

HAISCH: It seems very curious that the ratios of transition-region and chromospheric lines should show such random behaviour, when you would expect a temperature-stratified correlation of some sort or other. Could you comment on the lack of height dependence of your calculations, especially for N V, the hottest of your diagnostics, which is apparently uncorrelated with rotation?

BASRI: The height dependence of the slopes shows a general increase with temperature of formation, with the glaring exception of N V. I do not think that this is an effect of the data, and totally agree that this result is very surprising. I can offer no explanation for it at this time.

LINSKY: It is very important that we use diagnostic spectral features that clearly indicate the physical quantities that we want. I have been concerned for some time that the Ca II H and K lines may give uncertain estimates of chromospheric radiative loss rates because the correction for the photospheric light is large. Since the photospheric correction for the Mg II lines is far smaller, I suggest that the Mg II lines be used rather than the Ca II lines for intercomparison of radiative loss rates from different levels of a stellar atmosphere. Another concern is the N V flux. At the 6 Å spectral resolution of IUE, the 1240 Å spectral feature includes the N V doublet, some chromospheric lines like C I and S I, and the wings of the Lyman α geocoronal feature. Thus the N V "data" may not be an accurate measure of the N V stellar flux.

BASRI: I certainly agree that we should use these diagnostics very carefully. In particular, the behaviour of N V in our data certainly lends weight to your caution, and perhaps you have given the reason for its anomalies. Concerning Ca II and Mg II, I fully concur that photospheric corrections are both important and easier to handle for Mg II. What concerns me, however, is a growing number of indications in various work that the Mg II lines show less variability and sensitivity to activity changes in other diagnostics (like C IV and X-rays) than does Ca II. In this conference, for example, we have seen several correlations of Ca II with both X-rays and rotation, which are stronger than in our Mg II data. Studies of rotational modulation of Mg II have also often been less striking than for Ca II. I believe the time is ripe for a close examination of these two diagnostics. I am myself looking at Ca II for the same stars reported here to see if it really shows a period – activity connection contrary to Mg II.

GIAMPAPA: Are your Mg II flux measurements high or low resolution observations? Morossi and Ramella at Trieste found serious background correction problems due to halation effects, which increase with stronger Mg II emission.

BASRI: We are measuring only the flux above any underlying stellar continua or background signal. The corrections due to this subtraction are in any case small compared to the emission flux and should not have much effect on our log – log slopes.

CRAM: I am almost reduced to tears! We have beautiful correlations between Ca-line indices and periods (Noyes). We have bad correlations between Mg-line indices and periods. We think that Mg and Ca are formed in similar circumstances, and Linsky suggests that Ca, rather than Mg, is the line whose diagnostics are to be suspected. We have to be very worried about this problem, since so many of our inferences in this area depend on *empirical* correlations, for which we have no (or poor) theoretical models. It is very important to study the relation between Mg and Ca emission.

BASRI: I quite agree that this is worrisome and should be dealt with. I do not necessarily agree that Ca is the suspect diagnostic, but certainly a resolution is required. I am currently studying the Ca period – activity relation for these same stars, which may provide the answer. It is possible that either Ca and Mg are not as similar diagnostics as we think, or that the RS CVn chromospheres really do not share in the relations seen for the less active single star samples which are usually discussed.

GOLUB: I believe that we can put together results from several of the talks we have just heard in order to clarify at least a small part of this puzzle. Vaiana showed a few minutes ago that the X-ray flux goes with a high power (close to 3) of the Mg II flux. Fred Walter showed that, for the sample of stars you have been using, the X-ray flux varies inversely with the rotation period with a power of -1. Putting these results together, we expect a very shallow dependence of Mg II flux on rotation period, just as you are finding.

BASRI: My own data show, of course, the same steep dependence of X-rays on Mg II that you mention. The data are consistent with each other; the mystery is why Mg II is so shallow in light of the other reports that Ca II is well correlated with X-rays and magnetic field.