COMPARATIVE CHROMOSPHERIC AND CORONAL EMISSION FROM CLOSE BINARIES

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Observations of stellar chromospheres and coronae have become more feasible in recent years through the advent of shorter wavelength observations with the IUE and Einstein observatories. It has become increasingly obvious that activity in these parts of the stellar atmosphere is not a simple function of the two parameters on the usual H-R diagram, temperature and luminosity. On the contrary ranges of activity of greater than an order of magnitude can be seen in the chromospheric (Linsky et al. 1978, Stencel et al. 1981), transition region (Ayres et al. 1981) and coronal (Vaiana et al. 1981) emissions. There is a "third dimension" to the fundamental stellar parameters responsible for the intensity of stellar activity. Because such a range of activity is observed on the Sun to be correlated with the solar magnetic field, it is natural to suppose that this may be the other parameter. Unfortunately it is difficult to directly observe stellar magnetic fields, so we must also search for more indirect evidence that this is the case.

One of the more intriguing possibilities for establishing this connection is the apparent relation between stellar rotation and activity for various emission diagnostics. This was first suggested by Kraft (1967) for Ca II. The presumed physical connection between rotation and magnetic field is via the stellar dynamo. A recent extensive survey by Soderblom (1981) apparently confirms a linear relation between $v_R$ and Ca II emission for cool stars, but points out that age is a related variable which is difficult to separate from rotation. These two could have different physical significance if a primordial field plays a role in the dynamo, even though they are also related to each other. On the other hand, rather clear-cut evidence for a simple linear relation between x-ray surface flux and angular velocity was presented by Walter and Bowyer (1981) for the RS CVn stars, which all have similar evolutionary status. A quadratic relation between total x-ray luminosity and surface rotational velocity was found by Pallavicini et al. (1981) for a more diverse sample of stars. Thus, it appears that there may well be some connection between rotation (magnetic field?) and coronal activity, which is where one might best hope to see it because of the strong influence of the magnetic field on coronal structures.

In this paper, we report on preliminary results of an effort to extend the study of Walter and Bowyer to other close binary systems and to the many chromospheric and transition region diagnostics available to the IUE satellite. The binary systems offer the possibility of better determinations of stellar rotation and a wider spread in the magnitude of this rotational velocity than is available in a typical sample of single late-type stars. We have kept separate the
RS CVn stars, which are a relatively homogeneous group in spectral type and age, and other close binary systems. Our observations support this division. We report here primarily on our sample of stars for which we have both x-ray and Mg II resonance line data; a total of 31 stars of which 22 are RS CVn systems. The periods of these systems cover a wide range: from 0.7 day to 331 days. Most of the RS CVn stars are known to rotate synchronously so that the orbital period is the rotational period, but this assumption is more suspect for the very long period non-RS CVn systems.

The x-ray observations were made with the Einstein x-ray observatory, mostly using the IPC detector. Exposure times ranged from 600 to 4000 sec. Systematic uncertainties of about 20% may be present due to anode-to-anode gain variations and uncertainties in the channel boundaries; these uncertainties greatly exceed errors due to counting statistics. To compute x-ray fluxes, a factor of 2\times10^{-11} erg per IPC count was used.

The Mg II data were obtained with the LWR camera on the IUE satellite, mostly in the high resolution mode. We used the ripple-corrected reduced spectra which past experience leads us to believe are quite acceptable to measure the Mg II fluxes, the fluxes in the h and k lines were measured separately, then summed. Because of the presence of hotter componions in many of these systems, we use only the flux above the k1 and h1 minima, subtracting off any continuum below. We may therefore underestimate slightly the true chromospheric flux in some stars, but avoid larger errors due to improper inclusion of continuum flux. For several of the fainter RS CVn stars we only have low resolution spectra. These were treated in essentially the same manner as the high resolution spectra, except that the h and k lines are already combined by the poor resolution. Because of the inclusion of flux between the lines, and contamination from the nearby wings, we found the low resolution data to have systematically higher fluxes. We have several examples of both low and high resolution data on the same stars, and will determine a procedure for correcting this problem. In this paper, this data is plotted in parentheses and essentially ignored in the analysis. In order to remove the first order the effects of stellar distance and radius so as to have something indicative of stellar surface fluxes, we plot luminosity ratios.

In Figure 1 we show the x-ray rotation activity connection. Most of the points here are from Walter and Bowyer (1981) and show the linear relation that they reported. The filled circles are the RS CVn systems on which we will concentrate. There is scatter of an order of magnitude about this line which they attribute mostly to the intrinsic variability of these stars in x-rays. The crosses are the other close binaries, which show a tendency to lie a little below the RS CVn systems. These are mostly earlier spectral types, and several are more luminous than the typical RS CVn active component (which is an early K subgiant). It is interesting that even the very long period systems lie close to the general trend exhibited. The one anomalous point is 1 Gem (it is not really clear which star in this multiple system is the active one but the x-ray flux is definitely low).

When we look at a good chromospheric diagnostic, the Mg II resonance line flux, a different result emerges. Based on the x-ray data and the Skumanich and Eddy (1981) result for Ca II, we expect the same linear relation to appear. Instead (Figure 2) we see that while the fluxes for the RS CVn systems lie
Figure 1. The ratio of x-ray to bolometric luminosity versus orbital period for the RS CVn stars (filled circles) and other close binaries (crosses). There is a slope of $-1$ in this relation, indicating that x-ray surface flux is linearly related to stellar angular velocity for these stars.

Figure 2. Same as Figure 1 but for Mg II h and k emission line flux. It appears to be the same for all periods, but higher for the Rs CVn systems than the other close binaries. The open circles are low resolution data which probably need a systematic downward correction.
mostly within a factor of two of a linear relation, it has a slope of zero rather than the -1 for the x-ray data. These data are of higher resolution and much better calibrated than the Young and Koniges (1977) Ca II data used by Skumanich for his slope of -1. This does not mean that the Ca II relation he proposed is wrong, but we can say with reasonable certainty that it does not hold for the very similar chromospheric diagnostic Mg II. The Mg II data are in fact much more sensitive to variations in flux, both because of the better data quality and the greater contrast of the chromosphere in the UV. The RS CVn stars lie above the other close binaries (and well above most single stars), so their Mg II emission is enhanced, just not sensitive to rotation. Several possibilities for this suggest themselves. Perhaps the sensitivity of Mg II to magnetic activity has been saturated at this level of activity (but the T-Tauri stars lie above this level). Perhaps the chromospheric heating mechanism is not as strongly connected to the field as in the corona; the energetic requirements for it are certainly much greater. In that case, we really should not see a different relation for Ca II. At this preliminary stage we must leave this as an interesting puzzle.

We can avoid any question of dealing with stellar distance or radius by looking at the ratio of x-ray to Mg II flux measured at the earth. This tells us directly whether the chromosphere and corona obey the same relation with period. What we see in Figure 3 is that the linear relation between x-ray flux and period is improved by normalization to Mg II fluxes. We find a slope of 0.98 (correlation coefficient 0.9) for the RS CVn stars with periods greater than 1 day. The scatter in the x-ray relation alone has been greatly reduced (perhaps indicating that intrinsic variability was not its only source). It is actually quite surprising that the scatter should be so small, considering that none of the data was obtained simultaneously. The agreement of the long period close binaries is also rather remarkable, considering they are both different stellar types and need not be rotating synchronously.

One might suggest that part of the original scatter was due to errors in $L_{BOL}$, but this cannot be the whole story because the scatter was different for Mg II and x-rays. The implication seems to be that there is some intrinsic variation in the amount of energy passing through the chromospheres of these stars which doesn't have much to do with magnetic field, and that after accounting for that variation the amount which reaches the corona is a rather direct function of the magnetic field (it is unclear whether field strength or filling factor or both are important).

We can strengthen the argument that this result doesn't just reflect some insensitivity of the Mg II lines to the true situation by asking if some diagnostic of a region intermediate between the chromosphere and corona also shows an intermediate slope in the flux-period plot. We present results from a partial sample (all data have not yet been reduced) of the x-ray stars for which we have obtained CIV fluxes. The ratio of this transition region line to x-ray flux indeed shows an intermediate (0.55) slope, indicating that the agent connected with rotation has partially begun to control the energetics in the transition region.
Figure 3. The ratio of Mg II to x-ray flux as a function of period. There is a very good linear relation of slope 1, with less scatter than in the individual relations.

Figure 4. Same as Figure 3 but for CIV instead of Mg II fluxes. This shows that the transition region appears to be an intermediate case between chromosphere and corona.
We would like to emphasize that both the data reduction and our analysis presented here are preliminary. It will obviously be desirable to check these results against the several other diagnostic lines available in our IUE spectra. It would also be very interesting to perform a similar analysis for single stars and less active stars. Generalizations of these conclusions to those samples would be premature, as there is mounting evidence (cf. Vaughan 1980 and Soderblom 1981) that there may be at least two different behaviors among the chromospheric stars (young vs. old?, active vs. quiet?). Nonetheless, we believe that this work will be very useful in evaluating the character of the rotation-activity connection and obtaining evidence on the nature of the heating mechanisms in stellar outer atmospheres.

REFERENCES