CONTACT BINARY STARS

A. K. Dupree
Harvard-Smithsonian Center for Astrophysics
Cambridge, MA 02138 U.S.A.

Abstract: Ultraviolet and X-ray surveys of the W Ursae Majoris type stars are reviewed. These systems exhibit extended coronas and transition regions that are confined close to the optically determined surfaces. Correlations of X-ray activity with period or rotational velocity indicate a turn-over or saturation of emission at the short periods or high velocities found in the W UMa-type systems. For a number of systems, ultraviolet emission appears to be anti-correlated with the strength of X-ray emission. These observations are discussed in terms of solar structures, activity, and evolution.

1. INTRODUCTION

Contact binary stars of the W Ursae Majoris type are eclipsing systems composed of cool dwarf stars, with orbital periods of less than one day. The two components are spectroscopically similar in the optical spectral region although their masses are not equal. Mass ratios, M_2/M_1 can range from 0.5 to 0.1. It is generally thought that both components are contained in a common envelope, and the more massive component generates most of the luminosity of the system which is then transferred to the outer envelope of the secondary.

Some of these systems show period changes either of an abrupt or gradual nature, and the light curves can change in character. It is possible that some form of surface activity is present (Hall 1976; Guinan 1982).

These systems are believed to evolve toward lower mass ratios, higher effective temperatures and longer orbital periods. There may be loss of angular momentum from a system due to braking by a stellar wind. It has been suggested from theoretical calculations (Webbink 1976) that the final state of W UMa type binaries is a rapidly rotating single giant star as the more massive star engulfs its companion. Stars of the FK Comae class may represent such a final state (Bopp and Rucinski 1981; Bopp and Stencel 1981).

P. B. Byrne and M. Rodonò (eds.), Activity in Red-Dwarf Stars, 447–461.

The discovery that W UMa stars are a rich source of X-ray (Carroll et al. 1980) and ultraviolet emission (Dupree et al. 1979, 1980) enables the study of stellar activity under extremes of physical conditions and the definition of the influence of rotation on radiative emission levels. It is also of interest to investigate the extent of validity of analogies to solar atmospheric structures. This review will highlight the ultraviolet spectroscopic survey of W UMa systems made with IUE (Dupree and Dussault 1982; Rucinski and Vilhu 1982; Eaton 1982), and the X-ray survey undertaken with the HEAO-2 ("Einstein") satellite by Cruddace and Dupree (1982).

2. ULTRAVIOLET OBSERVATIONS OF W UMA-TYPE SYSTEMS

Ultraviolet observations of the short period binary systems VW Cep and 44 Boo were undertaken with the International Ultraviolet Explorer (IUE) satellite (see Dupree et al. 1979) immediately after the discovery by Carroll et al. (1980) that VW Cep was a source of X-rays.

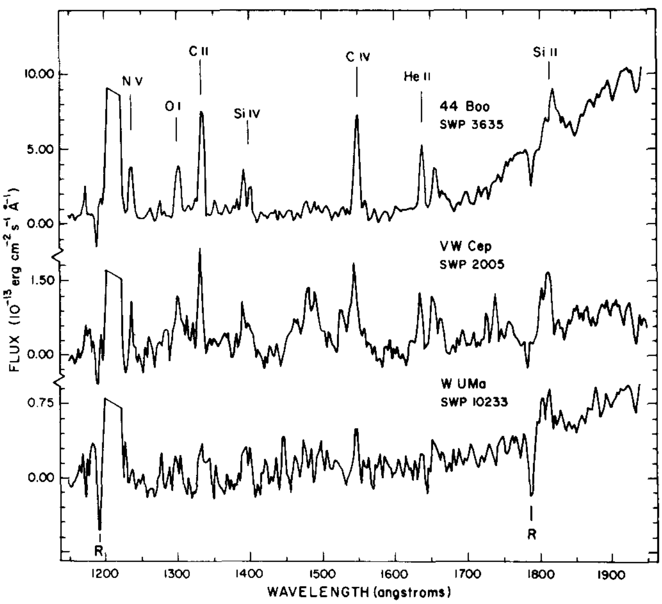

Figure 1. IUE spectra of three W UMa type systems: 44 Boo (P = 0.27 days); VW Cep (P = 0.28 days); and W UMa (P = 0.33 days). R denotes a fiducial mark on the camera faceplate (reseau). The emission feature at 1216 A is due principally to geocoronal Lyman-α and has been truncated. 44 Boo shows an increase in flux at long wavelengths. This emission arises from the companion star in the triple system. (From Dupree and Dussault 1982).

Subsequent to these initial observations, a number of systems have been measured with IUE by various authors (Dupree 1980; Rucinski and Vilhu 1982; Eaton 1982).

Short wavelength IUE spectra cover the range 1150 - 1950 A and sample spectra are shown in Figures 1 and 2.

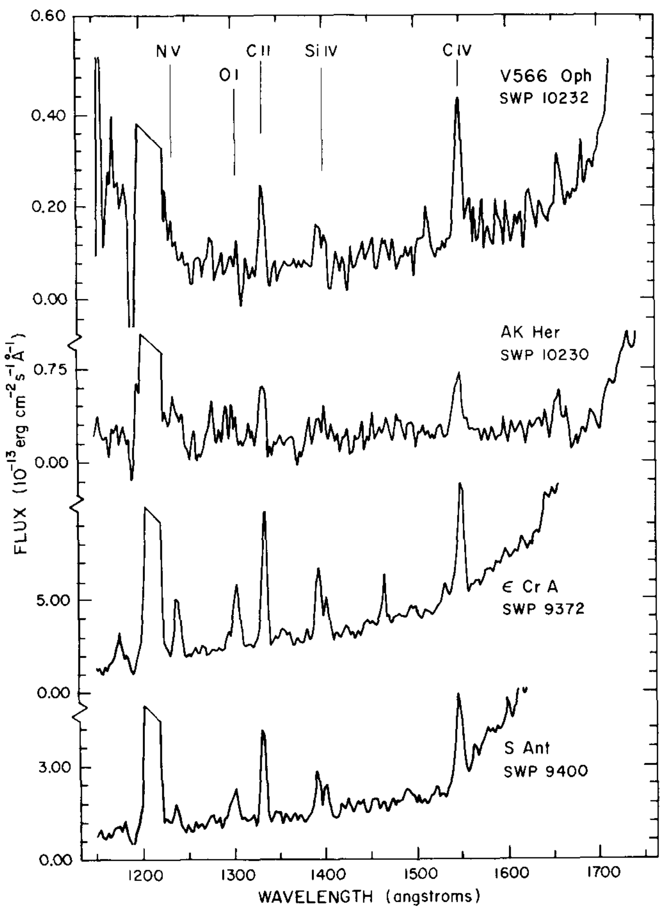

Figure 2. IUE spectra of three long-period W UMa systems: V566 Oph (P = 0.41 days); AK Her (P = 0.42 days); ε CrA (P = 0.59 days); and S Ant (P = 0.65 days). The systems of longest period, ε CrA and S Ant show the continuum increase longwards of 1500 A that is typical of hotter stars.

All of the systems show the typical strong series of emission lines, C II, Si IV, C IV, and N V that are present in single dwarf stars. A

https://doi.org/10.1017/S0252921100096470 Published online by Cambridge University Press

comparison of IUE spectra of cool stars in general can be found in

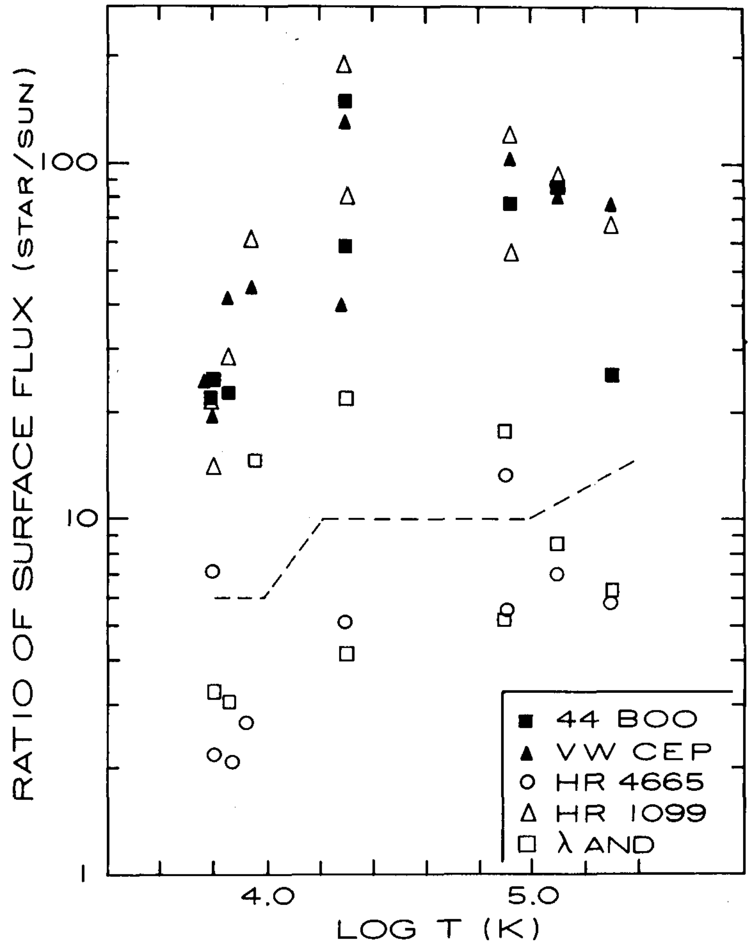

Figure 3. Homogeneous surface flux, in units of the quiet solar flux, for strong ultraviolet emission lines in five binary systems: 2 of W UMa type (44 Boo and VW Cep); 3 of RS CVn type (HR 4665; HR 1099; λ And). The emission lines are assigned to a typical temperature based on their formation in a collisionally dominated plasma. The broken line indicates the behavior of lines in a typical solar active region. Figure from Dupree et al. (1979).

several publications (Dupree 1980; Hartmann, Dupree and Raymond 1982). The relative intensities of the ultraviolet lines are similar to, but not precisely the same as, their relative intensities in a solar spectrum. There is clear indication of the presence of plasma having temperatures up to and including 2 x 10^5 K. The He II line at 1640 A

https://doi.org/10.1017/S0252921100096470 Published online by Cambridge University Press

is strong in the shortest period systems, 44 Boo and VW Cep. This is of interest because the line is thought to be produced in part by recombination following photoionization of helium by an X-ray continuum (Hartmann _et al_. 1979,1982); these two systems have the strongest X-ray flux. The longest period systems, although thought to be evolved, do not exhibit the characteristic strong O I line typical of giant stars with extended atmospheres where the O I is believed to be strengthened by fluorescence with Lyman-β.

It is particularly interesting to evaluate the surface flux of the emission lines (Figure 3).

For the two short period systems in Figure 3, the behavior of their emissions is similar in character to that found in solar active regions and RS CVn stars, namely an increasingly enhanced surface flux with increasing temperature of formation. It is the helium transition at 1640 A that provides the high points at a temperature of 4.5 dex K.

Most noteworthy is the enhancement of the surface fluxes in the short-period systems relative to those at longer period (Dupree _et al_. 1979). The RS CVn binaries have periods of 64 days (HR 4665) and 54 days (λ And, photometric period). It is only the short-period member of the RS CVn class HR 1099 (2.8 days) that possesses fluxes of commensurate value to the W UMa binaries. Rotation is a clear determinant of radiative losses.

Some of the brightest systems can be measured spectroscopically in the ultraviolet in a time short as compared to the orbital period. The flux variation in a number of lines has been measured for four systems in the low resolution mode of IUE. Two of the systems are bright enough to allow high dispersion spectra to be obtained at various phases. A typical light curve for ε CrA is shown in Figure 4.

Ultraviolet line emission is visible at all phases, and the variation of the emission is similar to the optical variation. The extension of the atmosphere is then similar to the optically determined surfaces. The depth of the ultraviolet primary minimum is comparable to that in the optical, and it appears that the depth of the minima are more nearly equal in the ultraviolet. High resolution ultraviolet spectra of the Mg II emission have been obtained from two systems with enough time resolution to separate the component stars. Both 44 Boo (Dupree and Preston 1980) and ε CrA (Dupree and Dussault 1981), when observed at elongations show two distinct Mg II features which are attributable to the individual stellar components of the binary. Moreover, their fluxes are in the ratio of apparent surface areas of the two components and the individual line widths are broadened consistent with that expected from synchronous rotation.

Thus the general behavior of the ultraviolet emissions is consistent with the optically determined physical parameters of the stars. The level of radiative losses or activity is substantially above that

https://doi.org/10.1017/S0252921100096470 Published online by Cambridge University Press

found in single stars of similar effective temperature and gravity.

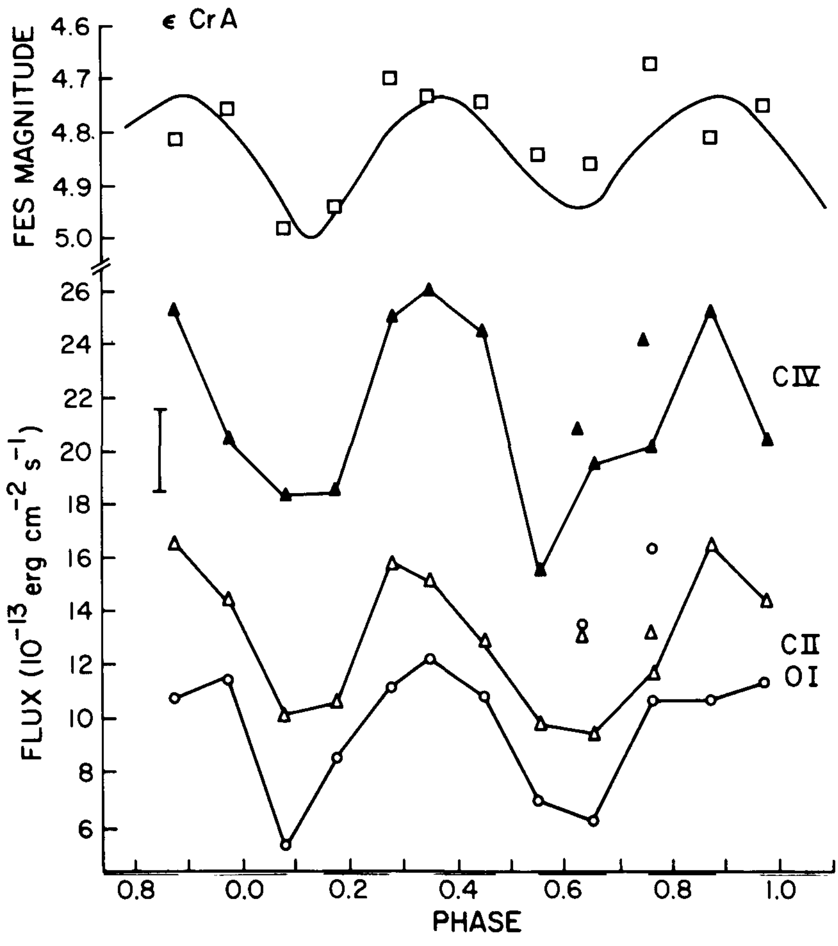

Figure 4. The light curve of ε CrA in a number of ultraviolet emission lines during a single epoch. The fine error sensor (FES) of IUE was used to determine the visual magnitude of the system immediately prior to each exposure. Symbols unconnected by lines represent spectra taken at other epochs. (From Dupree and Dussault 1981).

3. X-RAY OBSERVATIONS

A survey of 17 contact binary systems was carried out by Cruddace and Dupree (1982) using the Imaging Proportional Counter (IPC) of the HEAO-2 ("Einstein") Observatory as Guest Investigators. The stars in the survey represented a variety of short and long period systems. A total of 14 stars was detected. The X-ray luminosities of these

https://doi.org/10.1017/S0252921100096470 Published online by Cambridge University Press

systems (see Figure 5) span $\sim 10^{29}$ to $10^{30.2}$ erg cm^{-2} s^{-1}.

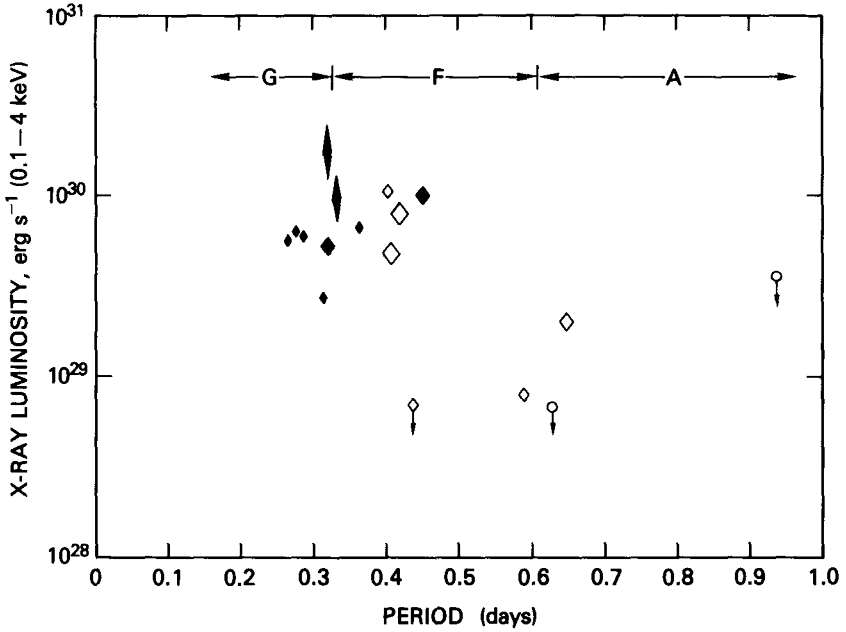

Figure 5. The X-ray luminosity of contact systems as a function of orbital period. The filled symbols represent the W-type systems; the open triangles denote the A-type binaries, and the open circles are the hot early type contact systems. The vertical extent of the symbols results from the uncertainty in distance (From Cruddace and Dupree 1982).

These values are in excess of the X-ray luminosities of single stars of similar effective temperatures as found in the Center for Astrophysics survey (Vaiana et al. 1981), and also exceed the X-ray luminosity of dwarfs in the Hyades (Stern et al. 1981) at the same spectral type. There is a clear dependence of X-ray luminosity on orbital period; the short period systems exhibit a generally higher luminosity than those of longer period. The data are insufficient to distinguish between a continuous or bimodel distribution of X-ray luminosity with period.

A quantity of interest is L_X/L_{bol} as a function of orbital period (see Figure 6) for it eliminates the uncertainty in distance.

The contact W UMa systems do not show a continuous extension of the L_X/L_{bol} relation from the RS CVn stars. As the orbital period

https://doi.org/10.1017/S0252921100096470 Published online by Cambridge University Press

shortens, there is a turnover of the L_X/L_{bol} dependence upon period - as if a saturation of flux occurs towards short periods. The position of the turnover may be associated with spectral type, but the data are too scanty to define this (Rucinski 1983; Cruddace and Dupree 1982).

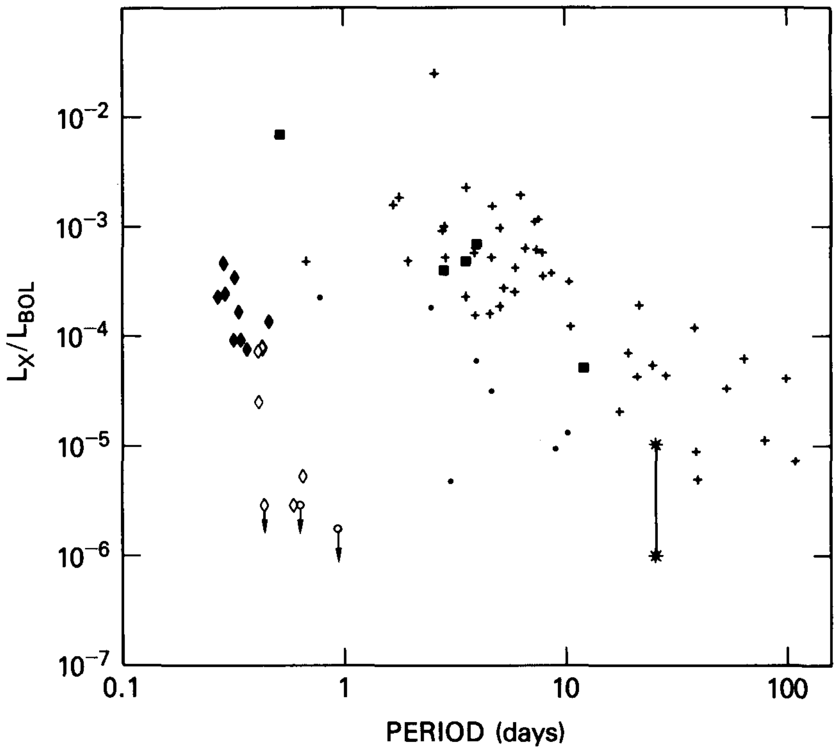

Figure 6. The quantity L_X/L_{bol} as a function of orbital period for the contact binaries (filled and open diamonds; open circles), RS CVn stars (plus marks) from Walter and Bowyer (1981), single F and G dwarfs (filled squares and dots respectively) from Walter (1981), and the Sun in an active and quiet state (stars).

Long and continuous measurements of the X-ray flux allowed a complete orbital period to be monitored in VW Cep (Dupree and Cruddace 1982). This demonstrated (see Figure 7) that X-rays are present at all phases suggesting a global distribution of hot plasma. There is not any well-defined enhancement at a repeatable phase which might be identified with long lived star spots or a splash-down region where mass transfer is occurring. The X-ray modulation clearly does not follow the optical light variation indicating that the corona is much larger than the scale of the optically determined system. The enhancements appear to result from short-term enhancements having a time scale on the order of the orbital period. The behavior at orbital phase 0.3 exhibits this short-term variation with a maximum enhancement on the order of a factor of two.

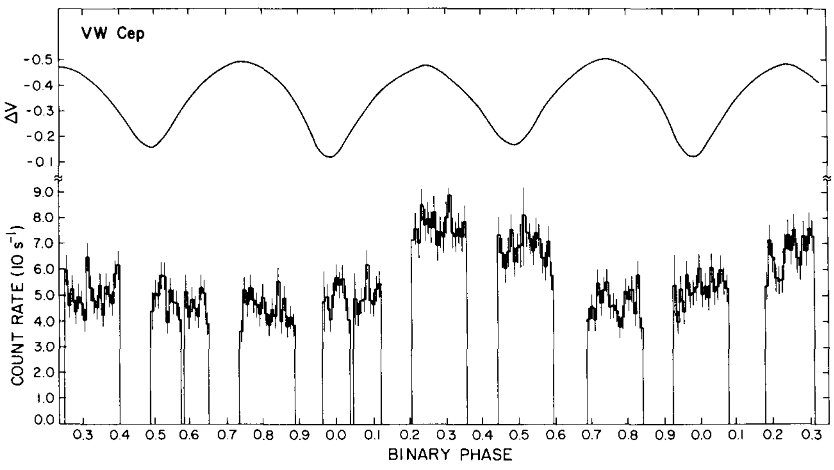

Figure 7. A continuous measurement of VW Cep through two orbital periods. The optical light variation is indicated by the top curve; the IPC count rates are given below where the lack of data corresponds to Earth occultations or data dropouts. (From Dupree and Cruddace 1982).

4. ATMOSPHERIC STRUCTURE

We can investigate whether there are any similarities between the structures suggested by these ultraviolet and X-ray observations and those familiar to us from the Sun. A useful quantity is the relative amount of hot plasma over the decade in temperature 2×10^5 to 2×10^6 K. This can be evaluated observationally using the N V and X-ray emission; simple loop models also predict this ratio. A summary of observations of various stars is shown in Figure 8.

Dwarf stars, the short period W UMa systems (the W-types), and RS CVn systems lie on the same theoretical relation as the Sun, and these three have a generally increasing scale of emitting material as expected from their luminosity class. Emitting structures of the short period W UMa binaries appear to be similar to coronal structures found on the solar surface.

Evolved stars such as field giants, the Hyades giants, and the hybrid supergiants show a deficit of high temperature material as do the long-period (A-type) W UMa stars. This suggests that the atmospheric structure of the long-period contact binaries is similar to that of

https://doi.org/10.1017/S0252921100096470 Published online by Cambridge University Press

more luminous stars, even though the contact binaries are relatively close to the main sequence. The response and evolution of an atmosphere may proceed more rapidly for a star in a binary system. Stellar winds are likely to be enhanced, a phenomenon known to cause a depletion of high temperature material, as found in solar coronal holes.

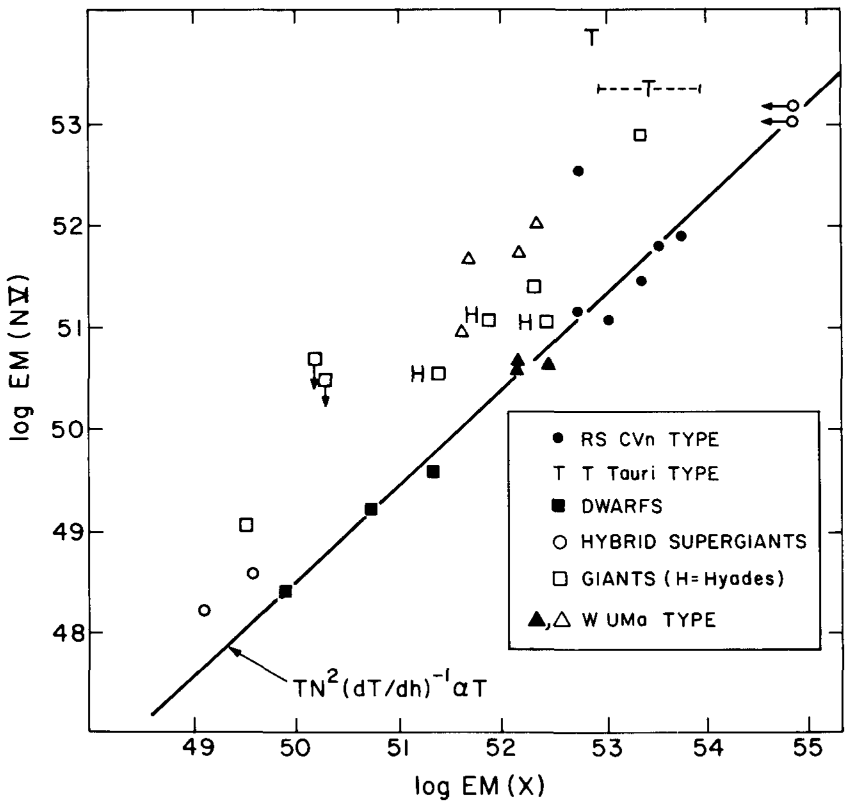

Figure 8. Emission measures as defined by N V and X-ray fluxes for stars of various classes. W-type contact binaries are noted by filled triangles; the A-type binaries are marked by open triangles. The Sun in an active and quiet state is indicated by the open circles. The straight line is the theoretical relation predicted by standard loop models. (From Hartmann, Dupree, and Raymond 1982, and Dupree 1982).

Another indication of atmospheric structure may be found in the behavior of the C IV and X-ray luminosity (Figure 9) which is anticorrelated for seven systems studied both with IUE and in X-rays.

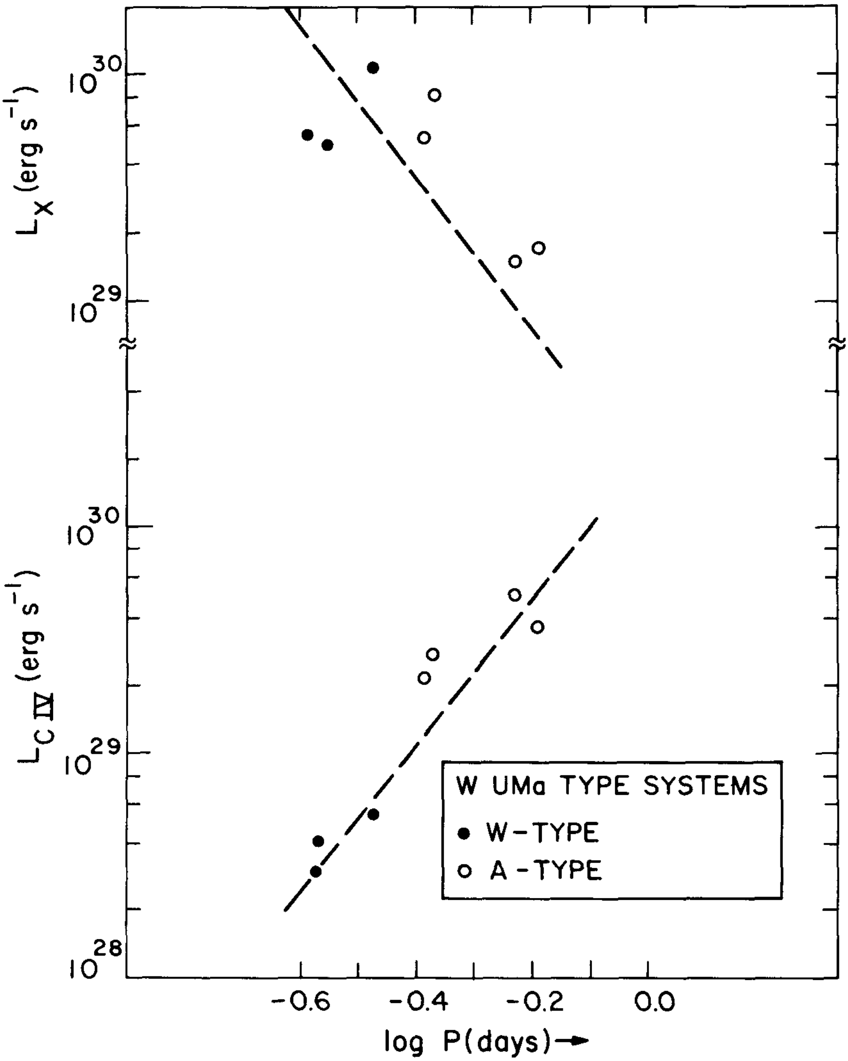

Figure 9. Total C IV and X-ray luminosity (erg s^{-1}) as a function of period for seven W UMa-type systems (Dupree 1982).

The X-ray luminosity decreases with increasing period, but the C IV luminosity does not follow suit, and increases with increasing period of rotation. This can be interpreted as a different heating mechanism for the corona as distinct from the atmosphere at lower temperatures. The results in Figure 9 may also reflect the response of an atmosphere to different magnetic field configurations, and the same total amount of energy might be required. The long-period systems exhibit a

https://doi.org/10.1017/S0252921100096470 Published online by Cambridge University Press

brightening in transition region lines, and relatively more material is at temperatures close to 10^5 K. However, the total radiative flux (here taken to be $L_X + L_{C\ IV}$) in the transition region and corona remains approximately constant.

5. DISCUSSION AND COMMENTS

Studies of these W UMa type systems reveal a high level of chromospheric and coronal activity from the majority of the objects. Stars in contact configurations emit enhanced X-ray and ultraviolet emission at all spectral types (here, generally late A through early K), and at all phases of their orbits.

Measurements of these binaries define the short period region of stellar activity and reveal that the extrapolations made from study of binaries not in contact do not predict the emission levels or behavior of the contact systems. Whereas rotation clearly enhances emission from stellar atmospheres - a fact long known from optical studies, and in general consistent with our understanding of the operation of the dynamo mechanism - the emission level does not continue to rise as the orbital period decreases below one day. Somehow, the dynamo "saturates". An explanation may reside in the structure of the subsurface layers, and the extent to which differential rotation is maintained.

Many other measurements need to be acquired. Very few observations have been made of these systems for any extended period of time so as to separate the transient behavior from the steady level, and to identify the extent of homogeneity of the surface emissions. A fundamental datum - the time of eclipse of the systems and the period - has not been recently measured for most of even the brightest systems. In one case, that of ε CrA, it was necessary to advance the published phase by 0.25 in order to force agreement with the IUE optical photometer.

The behavior of X-ray and ultraviolet emissions offers an opportunity to evaluate the effects of evolution upon the structure of a stellar atmosphere, and, due to the contact configuration, an accelerated form of evolution may occur.

This work was supported in part by NASA Grant NAG 5-87 to the Smithsonian Astrophysical Observatory and NASA Defense Purchase Requests H-43050B, H-43055B, H-46079B, and H-57323B with the Naval Research Laboratory. I am grateful to the Local Organizing Committee of this Colloquium for hospitality in Catania.

REFERENCES

Bopp, B. W., and Rucinski, S. M. 1981, in "Fundamental Problems in the Theory of Stellar Evolution", IAU Symposium No. 93, (D. Sugimoto, D. Q. Lamb, and D. N. Schramm, eds.), p. 177.
Bopp, B. W. and Stencel, R. 1981, Ap. J., 247, L131.
Carroll, R. W., Cruddace, R. G., Friedman, H., Byram, E. T., Wood, K. Meekins, J., Yentis, D., Share, G. H., and Chubb, T. A. 1980, Ap. J., 235, L77.
Cruddace, R. G., and Dupree, A. K. 1982, Ap. J., submitted.
Dupree, A. K., Black, J. H., Davis, R. J., Hartmann, L., and Raymond, J. C. 1979, in The First Year of IUE, ed. A. J. Willis, University College London, p. 217.
Dupree, A. K. 1980, in Highlights of Astronomy, P. Wayman (ed.), 5, 263.
Dupree, A. K. 1982, in Second Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun, M. S. Giampapa and L. Golub, eds., SAO Special Report 392, Vol. II, p. 3.
Dupree, A. K., and Dussault, M. 1981, Bull. A. A. S., 13, 873.
Dupree, A. K., and Dussault, M. 1982, in preparation.
Dupree, A. K., and Preston, S. 1980, in The Universe at Ultraviolet Wavelengths - The First Two Years of IUE, NASA Conf. Pub. 2171, p. 333.
Eaton, J. 1982, preprint.
Guinan, E. 1982, personal communication.
Hall, D. S. 1976, IAU Colloq. No. 29, "Multiple Periodic Variable Stars", (Reidel: Dordrecht), p. 287.
Hartmann, L. W., Davis, R., Dupree, A. K., Raymond, J., Schmidtke, P. C., and Wing, R. F. 1979, Ap. J., 233, L69.
Hartmann, L., Dupree, A. K., and Raymond, J. C. 1982, Ap. J., 252, 214.
Rucinski, S. 1983, this volume.
Rucinski, S., and Vilhu, O. 1982, preprint.
Stern, R. A., Zolcinski, M. C., Antiochas, S. K., and Underwood, J. H. 1981, Ap. J., 249, 64.
Vaiana, G. S., et al. 1981, Ap. J., 245, 163.
Walter, F. M. 1981, Ap. J., 245, 677.
Walter, F. M., and Bowyer, C. S. 1981, Ap. J., 245, 671.
Webbink, R. F. 1976, Ap. J., 209, 829.

DISCUSSION

Walter: I have two quick comments. The first is that you made some deal about the difference between the F and G stars when you plotted L_X vs L_{Bol}. It is very important to realize that you expect a difference because L_{Bol} has a T^4 term in it. So you have to be careful of what you are talking about. If you compare X-ray surface fluxes they may be the same whereas when you normalize to L_{Bol} they may be different.

Dupree: I concur but it is difficult to decide what to plot since

https://doi.org/10.1017/S0252921100096470 Published online by Cambridge University Press

surface areas, for instance, are not well determined.

Walter: With regard to the discontinuity at a period of 1 day, there is an interesting system, V471 Tau, which is not an RS CVn but has similar properties. It comprised a K dwarf and a white dwarf with an orbital period of 12 hours. So it is a very rapid rotator and in X-rays it looks just like and RS CVn star, falling on an extrapolation of the locus of the RS CVn's. Its period it is commensurate with of the WUMa systems. So this discontinuity at 1 day may not be a discontinuity but rather a change in the nature of the objects' convective zone or something. When dealing with non-single stars we may have very peculiar convective patterns.

Dupree: I concur. Nevertheless it is good to place them in perspective. But I concur, since these are contact systems we do not know much about their internal structures or atmospheres. So I agree, we may well be comparing "apples and oranges".

Linnell: From an evolutionary point of view it has become popular to think of evolution from the W subclass. It is important to note that Hoffman has identified a subclass whose light curve switches W-type to A-type. So a simple evolution from W to A subclass is certainly not entire picture. Webbink has pointed to a few systems in which the masses are large enough that you would never have expected them to pass through the W subclass at all and to others where the mass is so small you would never have expected them to have reached the A subclass.

Dupree: I concur. In every class of objects there are always some which are "schizophrenic". I was trying to term it in terms of physical quantities i.e. the mass and things like that. Let me make a point now which I had overlooked but which is of interest here. In evolutionary terms, it has been suggested that there is cannibalism among the dwarfs. If there is evolution from the short- to long-period systems and then to the coalesced giants, then the position of FK Comae suggests that a substantial restructing and enhancement of the X-ray luminosity may be necessary to agree with Webbink's evolutionary calculations.

Rucinski: I have one comment and one quetsion. The comment is that the discontinuity at 1 day is real. Some of these contact binaries arise from main sequence stars which come closer because of the constant loss of angular momentum. It is easy to show that this loss of angular momentum should speed up greatly as the stars come into contact. Once they are actually in contact the rate of loss of angular momentum should slow considerably. So it is probably quite natural that we have this break. My question is since contact binaries are under-active in X-rays, that is they lie lower than the extention of the RS CVn period relationships, do you think that this could be explained by the matter lost to the systems. This matter could be floating about and decrease the X rays.

Dupree: I have two comments. Firstly, the mass column density to all of these systems, determined spectroscopically, is of the order of 10^{18} cm^{-2} which is low. Secondly there is the question of whether we are really seeing the X-rays. In many of these systems we do not see the HeII (λ1640) line. We believe that this line is formed by recombination following ionization by X-rays. So this would be another indirect point against there being undetected X-rays. We also have looked at the Mg II line in high-resolution for signs of circumstellar absorption and not found any. There is... (part of comment lost)... in CrA at conjunction where you see an asymmetric profile which can be interpreted as indicating outflow.

Linsky: If one takes a limited sample of X-ray and optical data one could investigate whether the X-rays vary in phase or out-of-phase with the optical. Those who allocate X ray and UV telescope time ought to recognize that fact. Secondly, this is the only group of stars I know of in which the luminosity of the C IV line normalized to L_{Bol} decreases with decreasing period. Would you care to make a comment as to why this is?

Dupree: I would prefer to address this via the dependence of L_{CIV} on L_X. The ratio of L_X/L_{CIV} increases with decreasing period. It appears to be consistent with the evolution of an atmosphere in the sense that the CIV relative to X-rays gets larger. That is what we see in the evolved stars.

https://doi.org/10.1017/S0252921100096470 Published online by Cambridge University Press