RS CVn SYSTEMS : THE HIGH ENERGY PICTURE

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ABSTRACT

The discovery of X-ray emission from RS CVn systems by HEAO-1 and subsequent surveys by the Einstein Observatory have shown that these close binaries exhibit greatly enhanced coronal activity. Here we review the 3 main observational areas: (1) results of the X-ray surveys of RS CVn systems and other late-type stars which indicate how the X-ray luminosity is correlated with the binary period (and hence stellar rotation) and other coronal activity indicators. This will be discussed in the context of scaled models of the solar corona; (2) X-ray spectroscopy of the most active systems which show multi-temperature spectra and line emission consistent with solar abundances of the heavy elements; (3) observations of X-ray "flare-type" activity that has been associated with several RS CVn systems.

1. INTRODUCTION

Following the discovery by HEAO-1 (Walter, Charles and Bowyer, 1978) of strong soft X-ray emission from the RS CVn binary systems these objects have been the subject of intense scrutiny at all wavelengths. A "basic" RS CVn system consists of a KO IV star synchronously rotating (period $\sim$ 1-14 days) about a F-G main sequence star (Hall, 1976). Although of short period the system is detached and non-interacting. The photometric wave observed in the light curve (usually $\sim 0.1 - 0.2^m$) is almost certainly due to intense starspot activity on the cooler component (Hall, 1972), a model which explains many of the intriguing features of their activity. The main sequence requirement for the hotter component is relaxed for the longer period systems such as Capella.

Since neither component in the binary is degenerate the RS CVn systems likely represent the extreme end of the luminosity range ($\sim 10^{30-32}$ erg s^{-1}) for late-type stellar coronal X-ray emission. They are therefore of great importance for theoretical studies of coronal

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heating mechanisms assuming that the same process occurs in all stellar coronae. RS CVn's have been surveyed most extensively now by the Einstein Observatory (Walter and Bowyer, 1981 hereafter WB) as well as high quality X-ray spectroscopy being available for the brighter sources. In this review of the X-ray picture of RS CVn systems I will concentrate on; (1) the results of this survey and compare it with similar surveys that have been undertaken of less active systems. The X-ray activity has been correlated with other indicators of coronal/chromospheric emission; (2) the X-ray spectra of RS CVn and related systems which are interpreted as thermal emission from hot ($\gtrsim 10^7$K plasma; and finally (3) the (necessarily) more scarce observations of X-ray flares from these systems.

2. THE HEAO SURVEYS AND THE ROTATIONAL-LUMINOSITY RELATION

All RS CVn systems were observed as part of the soft X-ray (0.1 - 3 keV) all-sky survey of the HEAO-1 A2 experiment (Rothschild et al, 1979). However, because of the limited sensitivity of this non-imaging satellite only about 15 of the nearest or brightest RS CVn and related systems were detected (Walter et al, 1980) with soft X-ray luminosities ranging from $\sim 10^{30}$ to $\gtrsim 10^{31}$erg s^{-1}. The proportional counter X-ray spectra were consistent with thermal emission from plasma at T $\sim 10^7$K.

A more systematic survey of RS CVn systems was then undertaken by WB with the dramatically greater sensitivity of the Einstein observatory. Table 1 gives the observed properties of the stars in the HEAO-1 and Einstein surveys (from WB, Walter et al, 1980, Charles, Walter and Bowyer, 1979, Hoffleit and Jaschek, 1982 and Hall, 1976). From these data WB show that the luminosity function is the same for giants and dwarfs, and hence that they are equally luminous. However, there is a correlation of the form $L_x/L_{bol} \propto \Omega^{1.2}$ which is displayed in figure 1. The advantage of using L_x/L_{bol} is that, for similar effective temperatures, it is proportional to the surface X-ray flux and is independent of stellar radius and distance. The correlation is slightly less marked for the long and short period systems with power law indices of 0.8 and 0.6 respectively. WB interpret this relation as due to magnetic effects increasing with Ω and hence causing increased activity. Walter (1981) extends this work to rapidly rotating G and K stars with similar results. However, the G stars are about 10 times lower in L_x/L_{bol} than the K stars, thus indicating that the hotter (earlier) component in RS CVn's contributes only $\sim$10% of the X-ray flux.

Pallavicini et al (1981, hereafter PAL) have investigated the rotation - luminosity relation for all stellar types using mostly Einstein data. Their results for F7 - M5 stars are shown in figure 2 and gives $L_x = 10^{27}$ (v sin i)^2 erg s^{-1} which they find to be valid for giants and dwarfs. PAL cover a large range in L_x and the RS CVn's as a group are consistent with this relation, again

Table 1. : OBSERVED PROPERTIES OF RS CVn SYSTEMS

System	V_{max}	log L_x (erg s^{-1})	d(pc)	P_{rot}(days)	Sp	Notes
ζ And	4.1	30.14	31	38.9	K1IIe/?	
λ And	3.8	30.56	25	53.7	G8III-IV/?	
UX Ari	6.5	31.32	50	6.5	G5V/K0IV	HEAO-1
CQ Aur	9.6	30.94	220	10.7	G0/?	
SS Boo	10.2	30.80	220	7.6	dG5/dG8	
SS Cam	10.1	30.89	255	4.8	dF5/gG1	
12 Cam	6.2	31.18	180	79.4	K0III/?	
RZ Cnc	9.8	31.54	340	21.9	K1III/K4III	
AD Cap	9.3	31.28	250	3.0	G5/?	
RS CVn	8.4	31.27	150	4.8	F4III/K0IV	
39 Cet	5.4	31.18	59	-	gG5/?	
UX Com	10.8	31.51	350	3.6	G5-9/?	
RT CrB	10.2	30.74	360	5.1	G0/?	
WW Dra	8.8	30.84	180	4.7	sgG2/sgK0	
AS Dra	8.0	29.39	31	5.4	G/?	
RZ Eri	8.4	31.33	275	38.9	A5-F5V/sgG8	
σ Gem	4.3	31.31	59	19.5	K1III/?	HEAO-1
Z Her	7.3	30.3	85	4.0	F4V-IV/K0IV	
AW Her	9.5	30.94	315	8.9	G2IV/sgK2	
MM Her	9.8	30.76	190	7.9	G8IV/?	
PW Her	10.7	31.01	285	2.9	G0/?	
GK Hya	9.1	30.90	220	3.6	G4/?	
RT Lac	10.0	31.46	210	5.1	sgG9/sgK1	SSS*
AR Lac	6.9	31.18	40	2.0	G2IV/K0IV	HEAO-1
HK Lac	6.5	31.14	139	25.1	FIV/K0III	
RV Lib	9.8	31.06	276	10.7	G5/K5	
VV Mon	9.6	30.79	260	6.0	G0/?	
AR Mon	10.1	31.22	426	21.4	F-G/K0II	
II Peg	7.2	30.30	26	6.7	K2-3 IV-V/?	= HD224085
LX Per	8.1	30.80	145	8.1	G0V/K0IV	
SZ Psc	8.0	31.40	100	4.0	F8V/K1IV- V	
RW UMa	10.2	30.64	150	7.4	dF9/K1IV	
ε UMi	4.2	30.56	71	39.8	dA8-dF0/G5 III	
RS UMi	10.6	30.95	350	6.2	-	
ER Vul	7.3	30.19	36	0.7	G0V/G5V	
HR 1099	5.7	31.41	36	2.8	G5V/K0V	
HR 4665	6.3	31.41	130	64.6	K0III/?	DK Dra
HR 5110	5.0	31.11	53	2.6	F2IV/?	BH CVn
HR 7275	5.8	30.56	48	28.8	K1IV/?	
HR 7428	6.4	31.16	302	109.6	A0V/K2III-IIe	
HR 8575	6.4	30.23	69	17.8	K2III/?	V350 Lac
HR 8703	5.6	30.64	51	25.1	K1IV-IIIp/?	IM Peg
HD 5303	7.8	30.37	66	1.8	G0/?	
HD 155555	6.8	30.70	17	1.7	G5/?	
BD+61°1211	9.4	31.24	130	7.6	K0-1III-IV/?	

* both stars active

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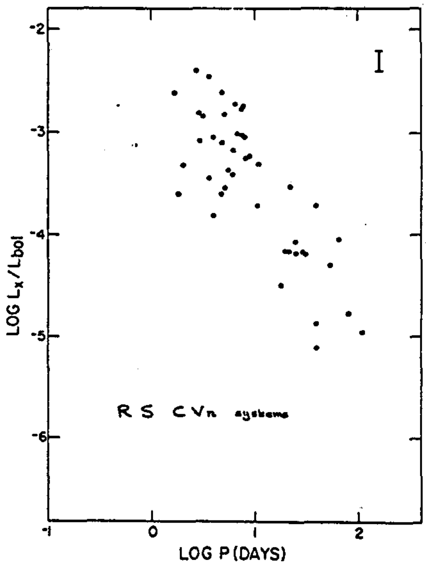


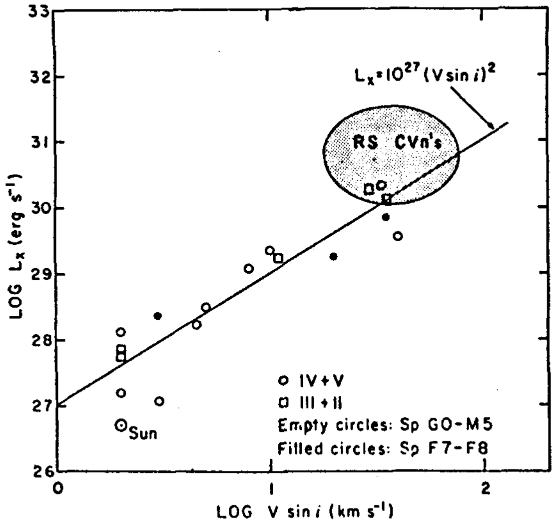
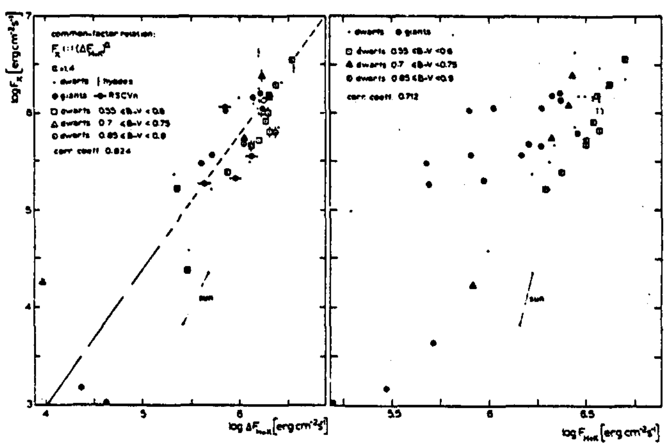


Fig. 1 : The WB plot of L_x/L_{bol} against rotational period.

Fig. 2 : The PAL correlation of L_x against rotational velocity for F7-M5 stars, including the RS CVn's as a group from fig.1.



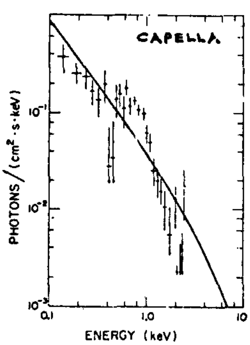


Fig. 3 : The SMZ correlation of surface X-ray flux with excess calcium flux is clearly shown in the left diagram compared to the much greater scatter of F_x against F_{H+K} on the right.

Fig. 4 : The original HEAO-1 LED spectrum of Capella (adopted from Cash et al, 1978) showing the Fe L emission blend at 0.85 keV.

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implying that enforced rotation leads to enhanced emission. However, the RS CVn's alone give only a low power correlation with v sin i.

Finally, Walter (1982) points out that a double power law gives a much better fit to the earlier (F8 - G2) stars Ω - L_x/L_{bol} relation with a break occurring near P = 10 days. The fall-off of L_x/L_{bol} at longer periods is dramatic. This period corresponds (Skumanich, 1972) to an age $\sim 10^9$ years and indicates that single stars remain active until that time.

3. THE X-RAY / CALCIUM II CORRELATION

Mewe, Schrijver and Zwaan (1981) used the Einstein Observatory to demonstrate a correlation between the X-ray surface flux, F_x, and the emission core flux in the Ca II H + K lines, F_{H+K}, for a small sample of cool stars (luminosity class III - V). F_{H+K} was used because, from observations of the Sun, it is found that chromospheric line emission originates at sites of strong magnetic fields. This work has been extended by Schrijver, Mewe and Zwaan (1982, hereafter SMZ) who use a larger sample (52) of stars covering a 4 dex range of F_x and which includes several RS CVn systems. SMZ find that the correlation between F_x and the calcium flux is greatly improved by plotting F_x against ΔF_{H+K} as shown in figure 3. ΔF_{H+K} is the difference between the observed flux and a lower limit to F_{H+K} that depends on spectral type (SMZ find that this lower limit flux is uncorrelated with the stellar X-ray emission). All the stars in their analysis (single giants, dwarfs, binaries and RS CVn's) follow the relation

$$F_x = 2.4 \times 10^{-3} \, \Delta F_{H+K}^{1.4} \quad \text{erg cm}^{-2}\,\text{s}^{-1}$$

SMZ find no correlation of magnetic activity with the structure of the star (i.e. M or R) but speculate that it may be related to rotation.

4. X-RAY SPECTRA : HOT CORONAL PLASMAS

Only a handful of these systems are bright enough for the HEAO-1 proportional counters to register spectral information. The first of these to be observed was Capella (α Aur) by Cash et al (1978). Although not strictly an RS CVn system (see Popper, 1980) it certainly displays the RS CVn phenomenon as does Algol (β Per; see White et al 1980). The HEAO-1 spectrum of Capella (figure 4) clearly shows the intense iron L emission blend at 0.85 keV which enables the spectrum to be described by an $\sim 10^7$K solar abundance coronal plasma. The other bright RS CVn system, UX Ari, was also consistent with a temperature of $\sim 10^7$K (Walter et al, 1978) although, because of the simplicity of the model, it was thought that iron was under-abundant.

4.1 Einstein SSS Observations : Medium Resolution Spectra

The Solid State Spectrometer (SSS; Joyce et al, 1978) onboard the Einstein Observatory was the first medium sensitivity detector to be employed for cosmic X-ray spectroscopy with a resolution at low energies substantially better than conventional proportional counters. The RS CVn and related systems were thus ideal targets for the SSS to investigate the relative line and continuum contributions. The SSS spectra of Capella, UX Ari, σ CrB, AR Lac and Algol (from Swank and White, 1980, Agrawal et al, 1981 and White et al, 1980) are shown in figure 5 together with the best-fitting thermal models. In all cases these models require 2 temperature components (assuming each to be in collisional ionisation equilibrium), the parameters of which are given in Table 2 (from Swank et al, 1981), and abundances within a factor 2 of solar. Figure 6 is a plot of the emission integral of each component versus temperature for all 8 RS CVn's observed. This shows that:

(i) the low temperature components are between 4 and 8 x 10^6K and have a narrow range of emission integrals ($\sim$1 dex) near 10^{53} cm^{-3};

(ii) the high temperature components have a much larger scatter in both temperature (26 - 93 x 10^6K) and emission integral ($\sim$3 dex);

(iii) Capella, UX Ari and AR Lac all show independent variations of the cool and hot components.

The prominent emission lines (due mainly to Fe, Mg, Si and S) are provided by the low temperature components, as most of these elements are fully ionised at the higher temperatures.

4.2 Einstein OGS Observations : High Resolution Spectra

The Objective Grating Spectrometer (OGS; Gronenschild et al, 1981) onboard the Einstein Observatory can give much higher resolution soft X-ray spectra than the SSS but has a much lower sensitivity. for this reason it has only been able to acquire a spectrum of Capella, and this is shown in figure 7. Gronenschild et al fit 2 temperature components to this spectrum of 5 and 10 x 10^6K. They are insensitive to X-rays of energy $>$1 keV and thus cannot detect the very high temperature components observed by the SSS.

5. STELLAR FLARES AND X-RAY TRANSIENTS

Long before RS CVn's were suspected of being X-ray sources they were known to exhibit large-scale radio flaring (Gibson et al, 1975). Indeed, a simultaneous radio, Hα, Lyα and X-ray outburst from HR 1099 was observed in 1976 (White, Sanford and Weiler, 1978) and a much more powerful and extended period of radio outbursts from HR 1099 was seen in 1978 (Feldman et al, 1978) but no X-ray observations could be made then. The HEAO-1 satellite enabled both the identification (Schwartz

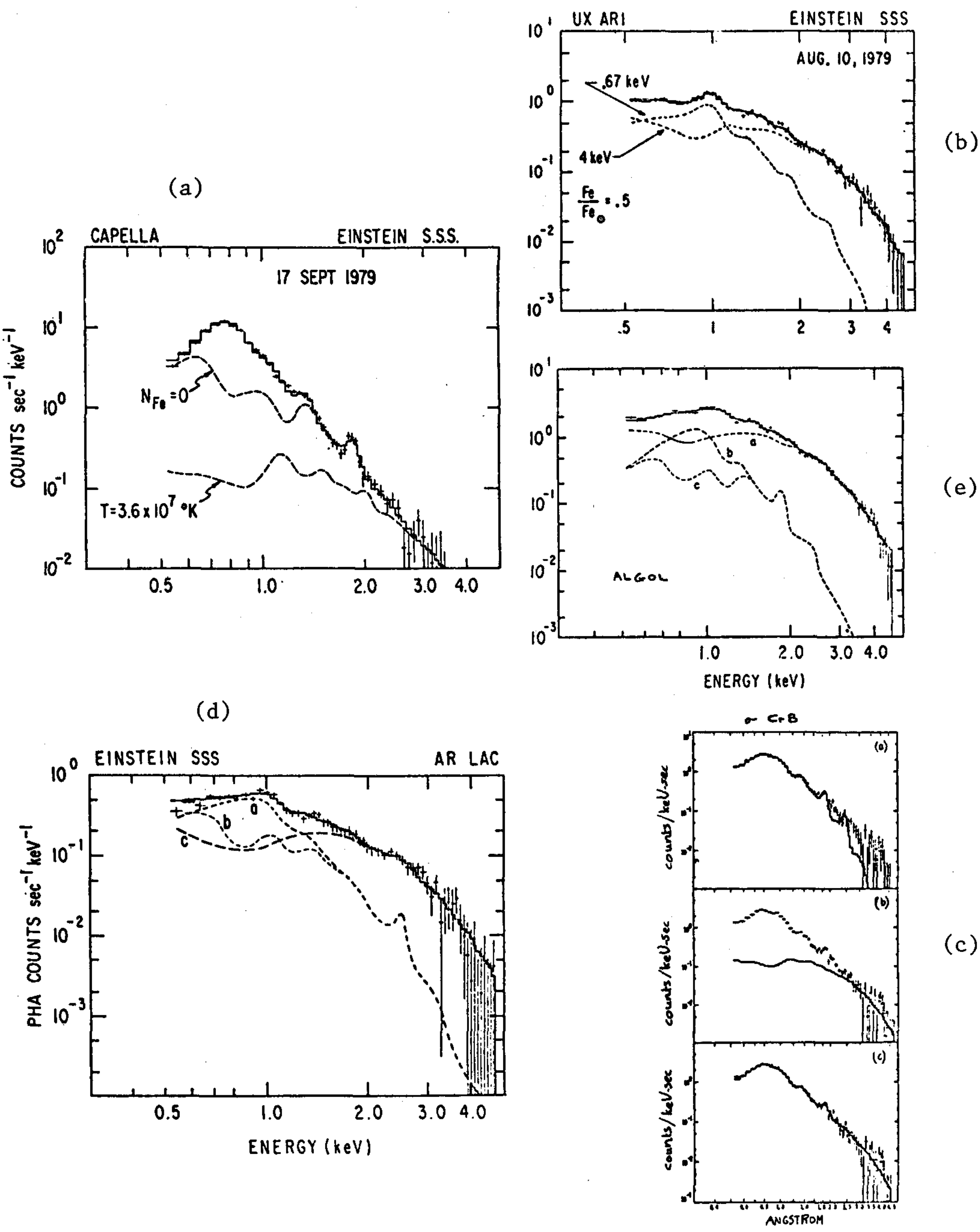

Fig. 5 : SSS spectra of (a) Capella,, (b) UX Ari, (c) σ CrB, (d) AR Lac and (e) Algol (adopted from Swank and White, 1980, Agrawal et al, 1981 and White et al, 1980). The individual temperature components of the best fit spectra are also plotted. The contribution of everything but Fe are shown for Capella, AR Lac and Algol.

Table 2 : X-RAY SPECTRAL PARAMETERS (from Swank et al, 1981)

Source	T_1 (10^6K)	T_2	log EM_1 (cm^{-3})	log EM_2
σ CrB	5.8	46	53.3	52.9
AR Lac	6.7-7.4	93-43	53.5	53.5-53.9
HR1099	6.7	48	53.4	53.7
Algol	7.0-8.2	33-48	53.1	53.5-53.9
RS CVn	7.0	96	53.4	54.0
UX Ari	7.5-7.9	31-65	53.8	54.0-54.5
λ And	6.8	36	53.3	53.3
Capella	4.0-6.0	30	53.0	52.3

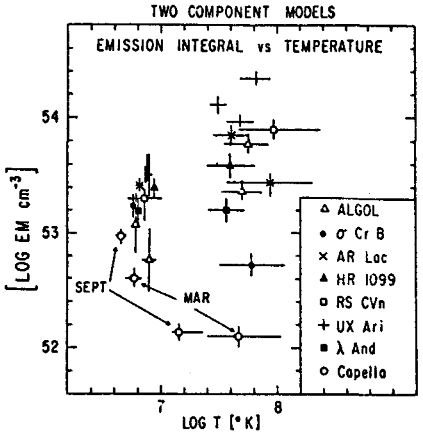

Fig. 6 : The Swank et al (1981) plot of emission integral against temperature for the 8 systems observed by the SSS. The low and high T components are clearly segregated (some sources were observed several times).

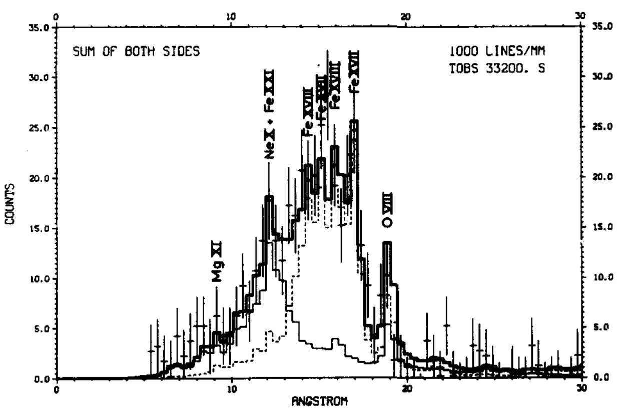

Fig. 7 : The Einstein OGS high resolution spectrum of Capella (adopted from Gronenschild et al, 1982). The model fit is the sum of 4 and 8 x 10^6K components and clearly shows individual ionic species.

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et al, 1979) and subsequent soft X-ray and optical study (Charles, Walter and Bowyer, 1979; Kimble, Kahn and Bowyer, 1981) of 2A1052 + 606 (= SAO 015338 = BD + 61°1211 = DM UMa), another X-ray source to exhibit flaring behaviour. A summary of all 6 such objects is given in Table 3. This flaring or transient-like activity may represent yet another extrapolation of the solar analogy. Of the stars in Table 3 it should be noted that:

(i) HR1099 has the strongest Hα emission of the objects in Hall's (1976) list;

(ii) the 3A1431-409 counterpart has much stronger (and steady) Hα emission than HR1099 (Booth & Charles, 1982);

(iii) BD+61°1211 and HD 224085 have much larger amplitude photometric waves ($\Delta V \sim 0.3$; Kimble et al, 1981; Rucinski, 1977) than normal RS CVn's (~ 0.1 - 0.2 mag) and both are asymmetric (see figure 8).

6. THE CORONAL AND STARSPOT MODELS

It was recognised soon after the discovery of X-rays from RS CVn's that some containment mechanism was required for the 10^7K and hotter gas (Cash et al, 1978; Walter et al, 1978). As pointed out by Swank and White (1980) the ratio of pressure scale height to stellar radius (assuming approximate hydrostatic equilibrium) is $H/R = 0.7\ (T/10^7)\ (R/R_\odot)\ (M_\odot/M)$ which is ~ 1 for Capella. Hence the gas is not controlled by the gravitational field. Instead Walter et al (1980) and Swank et al (1981) use the coronal loop model of Rosner, Tucker and Vaiana (1978 ; hereafter RTV; see also these proceedings) to interpret their data. In this model the X-ray emitting gas is confined at constant pressure to loops by magnetic fields. It is possible to use the RTV scaling law for loops of length $L = 5(T/10^7)^3\ p^{-1}$ to estimate the number of loops and area of the star covered by them given the value of pressure p. Since this is ~ 0.1 - 10 dyne cm^{-2} (for Capella, λ And and UX Ari) then L can be comparable to the stellar radius for the low T component but is comparable to the binary separation for the high T component unless the pressure is much higher.

It must be noted that if the X-ray emitting gas is confined to loops close to the surface of the active star then you would expect:

(i) an X-ray modulation of the light curve synchronised with the phometric wave;

(ii) X-ray eclipses.

The most extensive search for evidence of an eclipse has been made in AR Lac and none was seen (Swank & White, 1980). Nor have any phase-dependent effects been seen. The variations observed are thus presumed to be due to flares and these would arise from hot gas in the radio emitting region between the 2 stars (see Simon & Linsky, 1980).

To fit the observed photometric waves the starspots must cover between 6 - 18% of the surface of the active component (Eaton and Hall,

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Table 3 : RS CVn / X-RAY TRANSIENT AND FLARING SYSTEMS

X-ray source	Optical Star	L_x (max) erg s^{-1}	V_{max}	ref.
4U0336+01	HR1099	4×10^{32}	5.9	White, Sanford & Weiler, 1978
2A1052+606	BD+61°1211	10^{32}	9.4	Charles, Walter & Bowyer, 1979
H0123+075	HD8357	10^{33}	7.2	Garcia et al 1980; Hall et al, 1982
4U1137-65	HD101379	4×10^{31}	5.1	Garcia et al 1980
A0000+28	HD224085	10^{32}	7.2	Schwarz et al, 1981 (= II Peg)
3A1431-409	"V532 Cen"	$\lesssim 8 \times 10^{33}$	12.4	Booth & Charles, 1982; McHardy et al, 1982

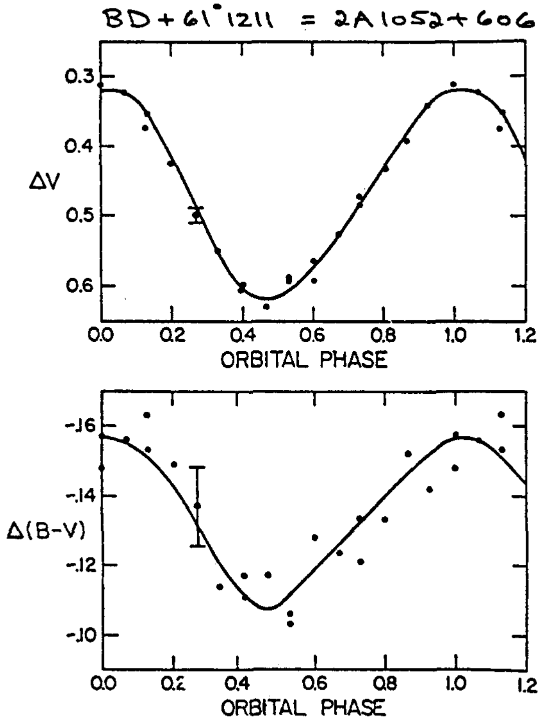

Fig. 8 : The large amplitude photometric wave and colour of BD+61°1211 (adopted from Kimble et al, 1981).

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1979; Dorren et al, 1980). Kimble et al (1981) show that this fraction must increase to ~1/3 in the case of BD + 61°1211 (with a lower limit of 16%) but again the starspot model does fit the observations very well (figure 8).

7. FUTURE OBSERVATIONS

The work I have tried to summarise above clearly shows the tremendous resurgence of observational interest in these very active cool stars at all wavelengths. As these proceedings show this has been matched by theoretical developments in coronal physics. At X-ray wavelengths the immediate future holds the bright prospect of the EXOSAT mission (due for launch Nov. 1982) which should be able to capitalise on the Einstein work shown here. The major areas of study include:

(i) more sensitive and longer observations of RS CVn's at high spectral resolution;
(ii) further study of RS CVn's with imaging systems to obtain crude spectra and variability information;
(iii) more extensive simultaneous observations with IUE and EXOSAT as well as ground-based optical and radio coverage.

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DISCUSSION

Budding: Have you looked at the Durney et al dynamo number parameter which will run together quantities like colour and rotation period. One has the impression that it may take out some of the scatter from some of your correlations. Secondly I question your lumping together of the RS CVn and Algol systems. I think that these stars are likely to be structurally rather different. They may be superficially similar in some respects but the Algol subgiants have been massive stars and are now in the thin shell-burning phase with highly collapsed cores. The RS CVn stars have just left the main sequence and are in the thick shell-burning phase.

Charles: I think you are probably right there. To take the second point first, I have not tried to say the Algols are RS CVn's. I rather want to say that the Algols exhibit the RS CVn phenomenon and that they fall below the RS CVn's activity relations. They are related but one does not know exactly how. So I present as much of the observational material as possible so that people can make up their own minds. I agree with you that they are different but on the other hand there are many similarities such as when one compares the X-ray spectrum of Algol with any of the RS CVn's. With regard to your first point, I did not actually do any of that work so I cannot comment fully. However I thought that something along the lines of your suggestion had been mentioned earlier on. Perhaps Fred Walter or Dr. Pallavicini would comment?

Catalano: I agree with you about the classification of secondary components on Algol-type stars but there is evidence that they show RS CVn features, at least from a photometric point of view. There are changes in the depth of eclipse in Algols, a time when we see the secondary, and these may be related to the out-of-eclipse variability in RS CVn's. We cannot see the wave variation outside of eclipse in the Algol because the primary is so bright. When one makes a Fourier-type analysis of the outside-of-eclipse light in Algols however there is some evidence of RS CVn-type variability also.