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X-RAYS FROM RS CANUM VENATICORUM SYSTEMS: A *HEAO 1* SURVEY AND THE DEVELOPMENT OF A CORONAL MODEL

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ABSTRACT

We present *HEAO 1* low-energy X-ray observations of 59 known or suspected RS CVn systems cited in the lists of Hall (1976), Eggen (1978), and the circulars of the Working Group on RS CVn systems of IAU Commission 42. Of these, 15 were detected with 3×10^{30} ergs s$^{-1} \lesssim L_x \lesssim 4 \times 10^{31}$ ergs s^{-1} and $T \sim 10^7$ K. The lack of detections of the other systems can be explained as being due to their greater distances or to reduced detector sensitivity. The data are used to argue against the validity of the minimum flux coronal models. We use a coronal loop model to derive expressions for the loop parameters in terms of observable quantities, and find acceptable solutions for RS CVn systems. We discuss the observed temporal variability and find that we can explain this variability simply in terms of the coronal loop model. We conclude that the difference between solar activity and that observed in RS CVn systems may be merely a matter of scale.

Subject headings: stars: binaries — stars: coronae — X-rays: binaries

I. INTRODUCTION

The *HEAO 1* A-2 low-energy X-ray sky survey[2] has shown that many of the brighter RS CVn binary systems are strong coronal X-ray sources. The UX Arietis system was discovered to be a strong source of soft X-rays from early *HEAO 1* data, and it was suggested that these systems might form a new class of soft X-ray sources (Walter, Charles, and Bowyer 1978*a*). A subsequent search of the first few months of *HEAO 1* low-energy data (Walter, Charles, and Bowyer 1978*b*, *c*) showed that most of the nearby RS CVn systems were sources of coronal X-rays. It was also noted that Capella, which had previously been identified as a soft X-ray source (Catura, Acton, and Johnston 1975) was a long-period RS CVn system.

Hall (1976) has defined RS CVn systems and the related long- and short-period systems. RS CVn systems have periods of 1^d–14^d, a hotter component generally late F to G V, and a cooler component K0 IV, and show evidence for bright chromospheres. Some are radio sources marked by strong episodes of flaring (e.g., Feldman *et al.* 1978; Gibson, Hjellming, and Owen 1975). The most intriguing, and perhaps the most fundamental property of RS CVn systems is the "photometric wave," attributed to a starspot-dominated hemisphere.

The canonical model of RS CVn systems (Hall 1972) is based upon the assumption that the wave is due to spots, or dark areas, on one hemisphere; Vogt (1978) has shown that the dark areas are similar to sunspots in temperature. Eaton and Hall (1979) have found that detailed modeling of a spotted surface can reproduce the light curves of these systems. The starspot model, via a solar analogy, provides a ready explanation for the enhanced chromospheric activity, and predicts strong coronal activity (cf. Walter, Charles, and Bowyer 1978*a*).

We report here on a search of the *HEAO 1* low-energy X-ray data for evidence of X-ray emission from a complete list of known RS CVn and related systems. The 59 systems have been taken from the lists of Hall (1976), Eggen (1978), and the circulars of the IAU Commission 42 Working Group on RS CVn binaries. We discuss the observations and discuss how these data fit in with various models of stellar coronae.

II. INSTRUMENTATION

A complete description of the *HEAO 1* cosmic X-ray experiment is given by Rothschild *et al.* (1979). The data presented here are from the low-energy detector (LED 1) most sensitive to point sources, with a field of view of 1°55 × 3°03 (FWHM). The detectors are propane-filled proportional counters with polypropylene windows and a nominal energy range of 0.15–2.8 keV; some of the observations were conducted with a lowered high voltage, which altered the energy range to 0.26–3 keV.

The data are taken with the spacecraft scanning in ecliptic latitude at a rate of 0°2 s^{-1}. Count rates are internally binned every 1.28 s. Sky coverage is not uniform as a result of operational difficulties during the mission. Most sources were scanned ~10 times, and for about half of the sources there exist two sets of scans, 6 months apart.

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[2] The *HEAO 1* A-2 experiment is a collaborative effort led by E. Boldt (GSFC) and G. Garmire (CIT), with collaborators at UCB, CIT, JPL, and GSFC.

III. LUMINOSITIES OF RS CANUM VENATICORUM SYSTEMS

The data, excluding those contaminated by the sunlit terrestrial atmosphere and the South Atlantic anomaly, were summed in 0°.5 bins in ecliptic latitude for this search. When available, data for three days centered upon source transit were used. The data set was fitted with a second-order curve representing the background plus the triangular collimator response function centered at the expected source position. The region of background data to be fitted, chosen to avoid other sources and confused regions, was generally about 10° in extent. The source significance was computed by forcing the amplitude of the triangle to zero and comparing the resulting χ^2 with the best-fit χ^2. This technique somewhat overestimates the uncertainties.

Fifteen of the 59 targets were detected; three more detections are marginal. Three targets could not be examined because of their proximity to bright sources (UX Com is obscured by the Coma Cluster, CG Cyg by the Cygnus Loop, and HD 158393 by 4U 1728 − 33).

The sources detected are given in Table 1; the upper limits are in Table 2. Except where noted, the luminosities are based upon a spectrum like that of UX Ari ($T = 10^7$ K, $N_x = 10^{19}$ cm^{-2}, no line emission). Distances are from Hall (1976), Eggen (1978), Hoffleit (1964), or Owen and Gibson (1978).

Ten regular-period RS CVn systems were seen, with luminosities varying from 3×10^{30} to 4×10^{31} ergs

TABLE 1

HEAO 1 SOFT X-RAY DETECTIONS OF RS CANUM VENATICORUM SYSTEMS

Name	L_x (ergs s^{-1})	Distance (pc)	Note	Date of Observation
		Regular Period (1^d–14^d)		
UX Ari	$2.1 \pm 0.15 \times 10^{31}$	50	1	1977 Aug 17–22, 1978 Feb 13–15
RS CVn	$6.24 \pm 3.0 \times 10^{31}$	145	2	1977 Dec 20–22
σ CrB	$3.92 \pm 0.54 \times 10^{30}$	21	3	1978 Feb 9–11
AR Lac	$1.48 \pm 0.3 \times 10^{31}$	50	4	1977 Dec 20–22
HR 1099	$1.20 \pm 0.15 \times 10^{31}$	33		1978 Feb 9–11
HR 5110	$3.0 \pm 0.9 \times 10^{30}$	46	5	1977 Dec 25–27
HD 5303	$1.41 \pm 0.41 \times 10^{31}$	66	6	1977 Oct 30–Nov 1, 1978 Apr 27–29
HD 155555	$3.16 \pm 0.74 \times 10^{30}$	17	9	1977 Sep 16–18, 1978 March 14–15
HD 224085	$3.98 \pm 1.2 \times 10^{31}$	26	7	1977 Dec 29
SAO 015338	$7 \pm 2 \times 10^{31}$	130	8[a]	1977 Oct 7–9
		Long Period (> 14^d)		
λ And	$1.85 \pm 1.0 \times 10^{30}$	24	10	1978 Jan 7–9
α Aur	4×10^{30}	14	11	1977 Sep 14–16, 1978 March 11–14
σ Gem	$2.06 \pm 0.31 \times 10^{31}$	59		1977 Oct 14–16, 1978 Apr 11–13
HK Lac	$1 \pm 0.4 \times 10^{32}$	150	12	1977 Dec 20–22
HR 4665	$8.4 \pm 2.0 \times 10^{30}$	47	13	1977 Nov 1–3, 1978 Apr 29–May 1
		Possible Detections (Regular Period)		
RW UMa	$4.35 \pm 0.31 \times 10^{32}$	150	14[a]	1977 Nov 24
		Possible Detections (Long Period)		
AR Mon	$6.1 \pm 2.7 \times 10^{32}$	495	15	1977 Oct 14–16, 1978 Apr 11–13
HR 7275	$6.3 \pm 2.9 \times 10^{31}$	250	16	1977 Oct 31–Nov 2, 1978 Apr 29–May 1

NOTES.—1. See Walter *et al.* 1978*a*. 2. A weak, 2.1 σ detection. The background is confused, but the source profile fits the collimator response. The detection is probably correct. See Walter *et al.* 1978*c*. 3. First reported in Walter *et al.* 1978*b*. The spectral types are earlier than most RS CVn systems, but this is probably a member of the class. Skillman and Hall (1978) report on a possible photometric wave in this system. 4. Confused with HK Lac. 5. The upper limit previously reported (Walter *et al.* 1978*b*) is in error. The region is slightly confused. 6. This source is near SMC X-1, but the best-fit position rules out this identification, as do the spectral parameters (see § IV). Noted by Eggen (1978) and Weiler and Stencel (1979). 7. This was observed on only one scan, about 2° off-axis, due to detector problems. Rucinski (private communication) has pointed out that this system may be very young, and may be more like the ξ Boo system than RS CVn's. Also known as II Peg. 8. The luminosity quoted is an average over three days, taken after the decay of the flare. This luminosity may be higher than the quiescent level. Only an upper limit was computed from the second pass. 9. The X-ray characteristics appear similar to those of σ CrB. A suspected RS CVn system, noted by Eggen (1978) and Weiler and Stencel (1979). 10. This source is > 2 σ at energies below 0.5 keV. It may be cooler than other RS CVn systems. Few scans of this source were obtained. 11. See Cash *et al.* 1978. 12. This source is confused with AR Lac, which is brighter. The limits are an overestimate of the errors on the luminosity; the source significance is $\gtrsim 3$ σ. 13. Distance estimate assumes $M_v = 2.0$, similar to λ And. 14. See § V. This is the luminosity during the flare. 15. The region is confused. The high luminosity suggests caution with this interpretation. 16. See discussion in § IV.

[a] See also upper limits in Table 2.

TABLE 2

UPPER LIMITS TO THE X-RAY EMISSION FROM RS CANUM VENATICORUM SYSTEMS

Name	$L_x(2\ \sigma) \times 10^{31}$ ergs s^{-1}	Distance (pc)	Note
	Regular Period		
CQ Aur......	< 14.0	220	
SS Boo......	< 9.0	220	
SS Cam......	< 11.0	255	
39 Ceti......	< 1.4	59	
FK Com.....	< 5.0 $D^{2\,a}$	...	
RU Cnc.....	< 6.4	190	
AD Cap.....	< 13.0	250	
RT CrB......	< 49.2	360	
AS Dra......	< 0.45 $D^{2\,a}$	...	
WW Dra.....	< 7.9	180	
Z Her.......	< 1.6	85	
AW Her.....	< 26.0	315	
MM Her.....	< 7.8	190	
PW Her.....	< 22.0	285	
GK Hya.....	< 7.0	220	
RT Lac......	< 14.0	205	
RV Lib......	< 34.0	276	
VV Mon.....	< 9.9	260	
LX Per......	< 1.7	145	1
SZ Psc.......	< 3.9	100	
TY Pyx......	< 1.5	85	
RW UMa....	< 19.0	150	
RS UMi.....	< 7.9	350	
HR 1362.....	< 0.63 $D^{2\,a}$	...	
HD 86590....	< 0.63	35	
SAO 015338..	< 6.0	130	2
	Short Period		
RT And.....	< 4.0	95	
SV Cam.....	< 1.3	85	
WY Cnc.....	< 3.7	160	
UV Psc......	< 6.6	125	
XY UMa....	< 2.1	100	3
ER Vul......	< 0.99	45	
	Long Period		
ζ And.......	< 0.33	31	
12 Cam......	< 0.63 $D^{2\,a}$	...	
RZ Cnc......	< 16.0	310	
RZ Eri......	< 5.0	105	4
ϵ UMi.......	< 1.0	71	
HR 7428.....	< 1.0 $D^{2\,a}$	...	
HR 8575.....	< 1.6	69	
HR 8703.....	< 1.9	55	

NOTES.—1. There is a 4 σ source near the location of LX Per (Walter *et al.* 1978*b*), but further analysis has excluded LX Per as a candidate. 2. See Table 1 and § V. 3. Distance from Geyer 1977. 4. We have excluded RZ Eri as the optical counterpart of 4U 0443 − 09.

[a] $D = d/(50\text{ pc})$, d = source distance.

s^{-1}. The luminosity of RS CVn is uncertain because of poor statistics, and that of SAO 015338 is probably not the quiescent level. Among the upper limits, only that of HD 86590 is less than 10^{31} ergs s^{-1}. We cannot rule out the possibility that all the others have X-ray emission of the luminosity of HR 1099.

Five long-period systems were detected. Three have luminosities of a few times 10^{30} ergs s^{-1}, while σ Gem is as luminous as most of the regular-period systems. Owing to source confusion, the luminosity of HK Lac is very uncertain. None of the short-period systems were detected, but the limits are not very significant.

Three other systems may have been detected. RW UMa may have flared during one scan (see § V). Sources detected at the positions of HR 7275 and AR Mon may not be associated with these stars, for reasons discussed in § IV and in Table 1.

The implication we draw from the data is that many, if not all, RS CVn systems are sources of coronal soft X-rays at a level of 10^{30}–10^{31} ergs s^{-1}. Since they all have active chromospheres and photospheres, it is reasonable to presume that they also have active coronae. Our data are insufficient to examine correlations between coronal luminosity and indicators of photospheric and chromospheric activity such as Hα emission and amplitude of the photometric wave.

IV. SPECTRA OF RS CANUM VENATICORUM SYSTEMS

Because of the low flux from most of the RS CVn systems, source confusion, or poor sky coverage, we were unsuccessful in extracting detailed spectra for any of the sources detected except Capella (Cash *et al.* 1978) and UX Ari (Walter, Charles, and Bowyer 1978*a*). As an alternative, we have used ratios of the broad-band energy channel count rates to constrain the spectral parameters.

Descriptions of the passbands and the detector efficiencies are in Rothschild *et al.* (1979). We use the count rates in the two layers of the proportional counter (M1, M2) which have different energy responses, the low-energy channel (W1) which has a high energy cutoff at 0.4 keV set by the electronics, and the total count rate S (= M1 + M2). In addition, we use the higher energy passband (0.4–2.8 keV) defined by M1 − W1. The hardness ratios M2/M1 and W1/M1 together define a unique value for the source temperature and absorption, if the shape of the spectrum (i.e., bremsstrahlung, plasma) is known. In the case of a plasma dominated by line emission at $T \sim 10^7$ K, the ratio W1/M1 can be used as a diagnostic for the presence of the Fe XVII–XVIII complex (see Raymond and Smith 1977) since the emission complex occurs entirely above the high-energy cutoff in W1. The spectral parameters of UX Ari and Capella are known independently, and are used as a reference for the other systems. Both have $T = 10^7$ K and N_X (the X-ray absorption column) $\lesssim 10^{19}$ cm^{-2}; Capella has emission from a solar composition plasma, whereas UX Ari is best described by a simple bremsstrahlung spectrum.

A comparison of these two sources with the others reveals the following two features:

a) Most have temperatures consistent with $T \sim 10^7$ K ($5 \times 10^6 \lesssim T \lesssim 2 \times 10^7$). The layer ratios in AR Lac may be explained by $T \sim 10^7$ K and $N_X \sim 5 \times 10^{21}$ cm^{-2}, which agrees with the value of $A_v = 0.17$ (Lacy 1979) toward this system. The lack of a detection of HR 7275 below 0.5 keV requires

$N_X \gtrsim 10^{22}$ cm^{-2}. The low significance of the detection, coupled with the apparently harder spectrum, argues for caution in the interpretation of this source.

b) Although the uncertainties in the count rates make it difficult to classify most systems, SAO 015338 appears to have a simple bremsstrahlung spectrum similar to UX Ari, while σ CrB and HD 5303 appear more like emission from a solar composition plasma, like Capella.

V. VARIABILITY

Three types of variability have been observed in the X-ray emission from RS CVn systems (Walter, Charles, and Bowyer 1979): flaring, short-term fluctuations in the level of the luminosity, and rotational modulation of the X-ray luminosity.

Flaring.—At least two instances of X-ray flaring of the RS CVn systems have been observed. White, Sanford, and Weiler (1978) reported an X-ray flare in HR 1099 coincident with a radio flare, and Walter, Charles, and Bowyer (1978*c*) have speculated that the bright X-ray transient, 4U 0316+01, which flared for a week (Forman *et al.* 1978), was a much larger flare, perhaps associated with activity on the scale of the 1978 February outburst (e.g., Feldman *et al.* 1978) in this system.

Analysis of the data on 2A 1052+606 = SAO 015338 (Liller 1978; Schwartz *et al.* 1978) during 1977 November 5–6 revealed a strong flare of maximum X-ray luminosity $1.7 \pm 0.17 \times 10^{32}$ ergs s^{-1} and duration $\sim 1^{d}5$ (Walter, Charles, and Bowyer 1979; Charles, Walter, and Bowyer 1979). The post-flare luminosity given in Table 1 is probably not the quiescent source intensity, and may be due to a slow decay of the flare activity.

Walter, Charles, and Bowyer (1978*b*) have reported observing a bright flare in RW UMa. We have reanalyzed this data and, although we cannot rule out a flare, its reality is now in doubt. There is no evidence for a source at this position from 1977 November 21 through 23. This region was scanned twice on 1977 November 24, with RW UMa approximately $1^\circ\!.6$ from the scan plane. A transient source at ecliptic latitude $44^\circ\!.7 \pm 0^\circ\!.25$ and ecliptic longitude $151^\circ\!.1 \pm 3^\circ$, about 1° removed from the position of RW UMa, was observed at $17^{h}56^{m}$ UT. The region was more confused at $13^{h}12^{m}$ UT, and can be well-fitted by a weaker source at the position of the transient, plus a source at the position of RW UMa. During this scan the field of view was within 6° of the edge of the Earth, and there is a possibility that the detector was viewing an enhancement along the Earth's horizon (Luhmann *et al.* 1979). However, we cannot discount the possibility that a flare, with $L_X = 1.9 \pm 0.44 \times 10^{33}$ ergs s^{-1}, was seen during this one scan.

From these observations, we conclude that, much like radio flaring, X-ray flaring is commonplace among RS CVn systems.

Short-term fluctuations.—The X-ray light curve of Capella (Walter, Charles, and Bowyer 1979) obtained by *HEAO 1* is the first strong evidence for variability in this source. The variability occurs on the scale of hours; the luminosity changes by up to a factor of 2 on subsequent scans. Contrary to the speculation of Mullan (1976), the average X-ray luminosity did not vary between 1977 September and 1978 March, during which time the phase of the photometric wave (Jackisch 1963) goes from 0.5 (minimum light) to 0 (maximum light). The observed rapid variability may be due to flaring on scales similar to that of the largest flares routinely observed in the Sun, as opposed to the types of flares observed in SAO 015338 and HR 1099. These variations agree with our conclusion (see § VI) that the emission in Capella is due to a small number of coronal loops; variations in the intensity of individual loops would then be expected to have a significant effect upon the total coronal luminosity.

Rotational modulation.—The light curve obtained for UX Ari during 1978 February shows that the source was not detected on three scans between binary phases 0.98 and 0.15, but was detected between phases 0.27 and 0.35 at a luminosity similar to that of 6 months earlier (Walter, Charles, and Bowyer 1979). Extrapolating from the data of Landis *et al.* (1978) and Weiler, Charles, and Bowyer (1978), we find that the photometric wave was at a minimum, i.e., the system was at maximum light, at about binary phase 0.1. The observations of 1977 August did not cover the phase of maximum light.

The 1978 February observations are readily explained by assuming that the X-ray emitting region is small compared with the size of the star, and that, in particular, the scale height of the emission is small. In this case, as the star rotates, the emitting region will be occulted by the body of the star once per rotation, for a length of time dependent upon the inclination of the system, the latitude distribution of the emitting region, and the scale height of the emitting gas. A limit on the scale height of the coronal gas is then

$$R < R_*\left[\frac{1}{\sin(90 - \iota + \theta)} - 1\right],$$

where R_* is the stellar radius, ι is the polar inclination of the star, and θ is the maximum latitude of the emission. From the data of Popper and Ulrich (1977), the inclination of UX Ari is $50^\circ \lesssim \iota \lesssim 64^\circ$. For $\iota = 55$ and $\theta = 30$, $R < 0.1\,R_*$. We can also estimate from the length of the occultation the longitudinal extent of the bulk of the emitting region. We find it to be $\lesssim 120^\circ$.

This result is consistent with the constant flux observed from this source during the 1977 August observation, which was centered near minimum light. Since the corona extends above the visible disk of the star and is optically thin, the corona will be visible for far more than one-half of the rotational period. The X-ray light curve should have a broad, flat maximum with a narrow minimum, which is in agreement with both sets of data when the migration of the wave between observations is allowed for.

We note that in this system, unlike others, the Hα emission appears to be localized on the dark hemisphere (Bopp 1979), a result which corroborates our observations if the chromospheric and coronal activity are related. From photometric observations it is not clear that all the spots are on the dark hemisphere, and there is evidence that when the wave disappears the spots spread themselves out around the star. However, the depth of the wave in UX Ari in recent years (cf. Weiler *et al.* 1978) requires a large inhomogeneity in the spot distribution and, by inference, in the coronal structure.

Steady sources.—During 5 days of coverage (1977 August 17–21), we see no evidence of variability in the X-ray luminosity from UX Ari. Chi-squared per degree of freedom to a linear fit at the weighted average intensity is 0.96. Similarly, no variability was observed in HR 1099 10 days before the 1978 February radio outburst, or in σ CrB (Walter, Charles, and Bowyer 1979).

VI. RS CANUM VENATICORUM SYSTEMS AND THEORIES OF STELLAR CORONAE

With these observations of RS CVn systems, the observed range of coronal emission measures from all classes of stars now extends over five orders of magnitude, from $\sim 10^{49}$ cm^{-3} for the Sun to $\sim 6 \times 10^{54}$ cm^{-3} for the brightest RS CVn systems, and coronal temperatures now range from 10^6 K to 10^7 K. We seek not only to use this wealth of new data to examine the validity of existing models of stellar coronae, but also to apply existing models of the solar corona to RS CVn systems in the hopes of deducing the physical characteristics of RS CVn coronae.

Mechanical models.—The emission in RS CVn systems is almost certainly associated with the cooler K0 IV component because this component shows the most surface activity. The model of Landini and Fossi (1973) predicts an X-ray luminosity of $\sim 5 \times 10^{27}$ ergs s^{-1} from a normal K0 IV star, well over three orders of magnitude below that observed. Their predictions that giants will not have coronae are in conflict with our observations of long-period RS CVn systems. This model certainly cannot account for our observations.

The minimum flux model (Hearn 1975) also makes specific predictions about the coronal luminosity for various spectral types. Mullan (1976) has applied this theory to giants and has predicted for Capella a coronal temperature of $\sim 5 \times 10^5$ K, a factor of 20 less than observed. The *HEAO 1* observations, taken together with those of Catura, Acton, and Johnston (1975) and Mewe *et al.* (1975), show conclusively that the 10^7 K gas is a quiescent, and not a flaring, corona, since the observations spaced over 5 years in time and 180° in orbital phase show similar luminosities.

More generally, the minimum flux model has difficulty because, for coronal temperatures of 10^7 K, the ratio of the radii of the critical point (where the gas velocity exceeds the escape speed) and the photosphere is much less than unity for giants and subgiants. At $T \sim 10^7$ K, all cooling should occur via stellar winds, and a stable corona could not exist, contrary to the observations. The model also assumes a spherically symmetric corona, which conflicts with our interpretation of the light curve of UX Ari.

Magnetic models.—Models based upon detailed observations of the solar corona require magnetic confinement of the coronal gas (e.g., Rosner, Tucker, and Vaiana 1978; Craig, McClymont, and Underwood 1978). Can a model of the solar corona be scaled up to the level of an RS CVn corona? Certainly the gross features (spotted active regions, active chromospheres) associated with the footprints of the coronal loops are present in RS CVn systems. We have applied the constant-pressure loop model of Rosner *et al.* to our data in an attempt to deduce the physical characteristics of RS CVn coronae implied by the model.

The basic parameters of the model are the length L of the magnetic flux loops and the number N of such loops. The observable parameters are the emission measure EM and the coronal temperature T. Rosner *et al.* derive a relation between the temperature of a coronal loop and its length and the gas pressure p,

$$T = 1.4 \times 10^3 (pL)^{1/3} ,$$

valid up to $T = 10^7$ K, which is based upon the cooling curve of a solar abundance plasma. In extrapolating from the solar regime to that of the RS CVn systems, we note that many RS CVn systems exhibit a deficiency of heavy elements (Naftilan 1975; Walter, Charles, and Bowyer 1978*a*), and thus the cooling curve is more like that of a simple bremsstrahlung and the relation for T is no longer valid. However, at $T \sim 10^7$ K, the emissivities of a solar composition plasma and a H-He bremsstrahlung differ by about a factor of 2 (Raymond and Smith 1977), so we can expect the extrapolation to be reasonably accurate.

The observed emission measure will be due to the superposition of N loops, all assumed to have similar lengths L and volumes $V = AL$, where A is the average cross-sectional area of a loop. If all loops have the same pressure, then only the longest loops will contribute significantly to the emission. Obtaining the density of the coronal gas in terms of T and L, and expressing AN as a fraction f of the surface area of the star,

$$L = 1.07 \times 10^9 (T_7)^4 (\mathrm{EM}_{54})^{-1} (R_*/R_\odot)^2 f$$

where R_* is the stellar radius.[3] The fractional area f is then given as a function of the coronal pressure p by

$$f = 340\, \mathrm{EM}_{54}\, T_7{}^{-1} (R_\odot/R_*)^2 p^{-1} .$$

We also wish to determine N, but this depends upon the geometry of the loops. If we assume that the radius of the loop can be expressed as αL, then

$$N\alpha^2 = 50(\mathrm{EM}_{54}) p (T_7)^{-7}$$

and

$$L = 3 \times 10^{11} (T_7)^3 p^{-1} .$$

[3] $Q_N = Q/10^N$.

TABLE 3

CORONAL PARAMETERS

Name	T (K)	EM (cm^{-3})	P (dyn cm^{-2})	f	L (cm)	$N\alpha^2$
UX Ari	10^7	4×10^{54}	10	16	3×10^{10}	2000
Capella	10^7	1.2×10^{53}	1.5	0.12	2×10^{11}	9
ξ Boo A	10^7	2.3×10^{51}	30	0.02	10^{10}	3
40 Eri A	10^7	4×10^{50}	30	0.01	10^{10}	0.6
Sun (quiet)	3×10^6	10^{50}	1	0.11	10^{10}	20
Sun (covered with plages)	10^7	4×10^{52}	10	1.3	3×10^{10}	20
Subgiant (covered with plages)	10^7	4×10^{53}	10	1.3	3×10^{10}	200

In Table 3 we present values of these parameters for UX Ari, Capella, and the Sun for comparison.

Weiler (1978) has reported a chromospheric pressure in UX Ari of ~ 10 dyn cm^{-2}. If this is the coronal base pressure, then we find that the loop length is $\sim 3 \times 10^{10}$ cm, similar to that observed in the Sun. The fractional area f is large, which indicates that the corona covers much of the surface area of the active chromosphere. In addition, f can be greater than unity because the average cross-sectional area of a loop is greater than the cross section at the base of the loop. The number of loops is on the order of 10^4. These values of f and N agree with the requirements of optical models (e.g., Vogt 1978; Eaton and Hall 1979) of $\sim 10^4$ spots covering a large fraction of the surface area of the dark hemisphere of the active star. If the spots are the footprints of the coronal loops, we require $\sim 2 \times 10^4$ spots on the dark hemisphere.

We find a different situation in Capella. For a coronal pressure of 1.5 dyn cm^{-2} (Haisch and Linsky 1976), $f \sim 0.12$ and $L \sim 2 \times 10^{11}$ cm, and N is then small, on the order of 10^2. This situation is then closely akin to the solar corona, where a few loops dominate the emission. The variability of Capella can then be readily explained as being due to the growth and decay of individual loops.

This scaling also seems to work for the less luminous systems 40 Eri (Cash *et al.* 1979) and ξ Boo (Walter, Charles, and Bowyer 1978*b*). We assume the emission in each case comes from the A component (G8 V in ξ Boo, K1 V in 40 Eri). Limiting L to the stellar radius provides a lower limit on p of ~ 6 dyn cm^{-2} for each system. If we assume $L = 10^{10}$ cm, as on the Sun, then $p = 30$ dyn cm^{-2} as in solar flare loops: N is small in any case. We predict that these two systems will be highly variable in their X-ray luminosity, and that they have high chromospheric pressures.

For comparison, we have included in Table 3 these parameters for the quite Sun, a hypothetical plage-covered Sun (Vaiana and Rosner 1978), and a hypothetical plage-covered subgiant. The latter bears strong resemblance to the less luminous RS CVn systems (e.g., HD 5303, σ CrB, HR 5110). This strongly suggests that the coronae of these systems are similar to those associated with solar plages. The more active RS CVn systems (e.g., UX Ari, RS CVn, AR Lac, HR 1099) may require an additional source of flux, perhaps from flaring regions. However, we emphasize that these coronae can be characterized by fairly long-lived loop structures without the need for continual flaring.

The model as extrapolated makes specific predictions for f, which is related to the fraction of the surface area covered by the footprints of the loops, or by spots, and $N\alpha^2$, a measure of the number of loops which depends on the geometry of the loop, in terms of three observable coronal parameters. The resulting values are self-consistent. The Sun and Capella have less active coronae, wherein N, f, and p are small, and L may be determined by the stellar size in some manner.

RS CVn systems appear to be an extreme case, where L is limited by the space available, since N is large and $f \sim 1$. In this model, RS CVn systems are predicted to have fairly constant X-ray luminosities, while the long-period systems with fewer loops would be expected to flicker.

On the basis of our data, there appears to be no fundamental distinction between the activity in RS CVn systems and that in the Sun. Since many late-type stars including RS CVn systems have stellar cycles (Wilson 1978), and even the Sun shows an active and an inactive hemisphere (Speich *et al.* 1978), RS CVn systems may just be an extreme case of normal late-type stellar activity.

VII. SUMMARY

We have presented observations of RS CVn systems from the low-energy X-ray detectors aboard *HEAO 1*. About one-third of the systems were detected, with 3×10^{30} ergs $s^{-1} \lesssim L_x \lesssim 4 \times 10^{31}$ ergs s^{-1}, and $T \sim 10^7$ K. The lack of detections of the other systems can be reasonably interpreted as being due to their greater distance or reduced detector sensitivity. We predict that most, if not all, RS CVn systems are coronal X-ray sources at a level of $\sim 10^{30}$ ergs s^{-1}.

Variability has been observed in some systems. Flaring appears commonplace. In Capella we have seen evidence for temporal changes in the corona on time scales of hours. We have placed a limit on the scale height of the X-ray emitting corona in UX Ari from an observed eclipse of the X-ray emission.

We find we cannot explain the data in terms of the minimum flux model of coronae. Models requiring magnetic confinement of the coronal gas have been applied, and can explain the observed emission measures, pressures, temperatures, and variability, and are in accord with the canonical RS CVn models. We have derived expressions for the fraction of the surface area covered by spots as a function only of observable quantities. We conclude that the difference between solar activity and RS CVn activity may be merely a matter of scale.

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