THE CORONAE OF RS CVn SYSTEMS

Frederick M. Walter, Philip A. Charles, and Stuart Bowyer
Space Sciences Laboratory
University of California, Berkeley 94720

1. INTRODUCTION

RS CVn systems [1] are close binaries consisting of two late-type stars, one of which has evolved to the base of the giant branch. In most cases, the systems appear to be the product of normal stellar evolutionary processes [2,3]. These systems have attracted much recent attention because they exhibit greatly exaggerated stellar activity in the form of strong chromospheric emission [1]. There is evidence that a large fraction of the surface is covered by dark spots [4]. They also exhibit radio emission [5,6], and quiescent and flaring soft X-ray emission [7-12]. If these stars are undergoing normal evolution, why then are they so peculiar?

It is possible that their abnormalities are no more than a gross exaggeration of the activity associated with late-type convective stars, such as the Sun. In these systems, the active star has been forced into synchronous rotation at the binary period, which is much shorter than that of most late-type stars. Presumably the speeding up of the rotation has some effect upon the dynamo processes that ultimately generate the stellar activity. We have studied the coronae of the brightest RS CVn systems using soft X-ray observations, and we report here on the relation between the coronal activity in RS CVn's and that in more "normal" stars.

II. EXPERIMENT AND OBSERVATIONS

These observations were undertaken using the Low Energy Detectors (LED) of the HEAO-1 A-2 Cosmic X-ray Experiment[1] [13]. The LED's are sensitive to 0.15 to 2.8 keV X-rays. The data were searched for evidence of X-ray emission from fifty-nine RS CVn's and related objects listed by Hall [1], Eggen [14], and the Circulars of the Working Group on RS CVn systems of IAU Commission 42. The data analysis and the results are fully described by Walter *et al*. [10].

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The fifteen positively detected sources are listed in Table 1 along with a probable detection of RW UMa [10]. The X-ray luminosities span an order of magnitude. The upper limits derived for the X-ray luminosities of the other sources are inconclusive since all but one are greater than 10^{31} erg s^{-1} indicating that these systems could well be bright X-ray sources but are too distant for detection with this experiment. Spectra of UX Ari [7], Capella [15], and broadband spectra of the weaker sources [10] show that all have temperatures of $\sim 10^7$K, but that some show no evidence for the line emission expected from a solar composition plasma. UX Ari appears underabundant in Fe by a factor of 30 relative to solar [7].

Table 1. Luminosities (.15-2.8 keV) of RS CVn Systems.

Source	L_x(x 10^{30} erg s^{-1})	Source	L_x(x 10^{30} erg s^{-1})
λ And	1.8 ± 1	HR 1099	12 ± 1.5
UX Ari	21 ± 1.5	HR 4665	8.4 ± 2.0
α Aur	4.0 ± .2	HR 5110	3 ± .9
RS CVn	62 ± 30	HD 5303	14 ± 4
σ CrB	3.9 ± .5	HD 155555	3.2 ± .7
σ Gem	21 ± 3	HD 224085	40 ± 12
AR Lac	15 ± 3	SAO 015338	70 ± 20 (flare)
HK Lac	100 ± 40	RW UMa	435 ± 31 (flare)

Three types of variability have been observed. Flaring, similar to radio flaring, on timescales of hours to days, appears commonplace [7,10,12,16]. Capella has been observed to vary by up to a factor of 2 on scales of hours [9,10], but no such variability is observed in UX Ari, HR 1099, or σ CrB. However, the emission from UX Ari was observed to decrease by at least a factor of three at the phase of maximum light; we interpret this to be an occultation by the body of the star of a corona localized above the spotted hemisphere. This observation allows us to put an upper limit on the scale height of the emission of $\sim$ 0.1 of the stellar radius, as well as limiting the longitudinal extent of the emission to $\sim 120°$.

III. CORONAL MODELS

We have attempted to model the emission in terms of a loop model of the solar corona [10], wherein magnetic flux tubes emanating from the stellar surface in the active regions contain the coronal gas. Starting from the empirical relation between gas temperature T, pressure p, and loop length L [17], we derive expressions for L, f, the product of the number of loops N and the average cross sectional

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area of a loop relative to the stellar surface area, and the number of loops N times a geometrical factor α^2 ($\alpha^2 L^3$ = loop volume) in terms of three observable quantities, T, p, and the emission measure EM.

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

$$f = 340 \; (EM_{54})(T_7)^{-1} \; (R_\odot/R_*)^2 \; p^{-1} \quad (2)$$

$$N\alpha^2 = 50 \; (EM_{54}) \; p(T_7)^{-7} \quad (3)$$

where R_* is the stellar radius, p is in dyn cm^{-2}, T_7 is in 10^7 K, and EM_{54} is in 10^{54} cm^{-3}. Values for these parameters are given in Table 2 for UX Ari, Capella, the active Sun and a hypothetical active Sun, entirely covered with plages [18].

Table 2.

	T	EM	p	f	L	$N\alpha^2$
UX Ari	10^7	4×10^{54}	10	16	3×10^{10}	1700
Capella	10^7	1.2×10^{53}	1.5	.12	2×10^{11}	9
"Plage" Sun	10^7	4×10^{52}	10	1.3	3×10^{10}	20
Active Sun	3×10^6	10^{50}	1	.11	10^{10}	20

IV. DISCUSSION

From Table 2, we find that UX Ari (and the other active RS CVn's) have f of order unity and N $\sim 10^4$. This indicates that the corona covers most of the active hemisphere, unlike in the Sun where the corona is localized above small fraction of the surface, and that there are a large number of starspots. This is in good agreement with the optical results that require a large number of spots covering a large portion of one hemisphere. Capella is less active, with many fewer loops. This is a possible explanation for the absence of variability in UX Ari; changes in the loop structure of Capella have a more noticeable effect upon the total X-ray luminosity. We note that were the number of loops on the active Sun to be increased by 10^3, then f would also increase and the parameters would be comparable to those of UX Ari. Indeed, were the surface of the Sun entirely covered with active regions, and were it a subgiant, its X-ray luminosity would be $\sim 2 \times 10^{30}$ erg s^{-1} [18], comparable to that observed in the less active RS CVn's

We conclude that the coronae of RS CVn's and that of the Sun may well differ only in scale. If so, the mechanisms at work in RS CVn's are similar to that in the Sun, except that the rate of magnetic flux tube generation has greatly increased, perhaps due to forced rapid rotation. Results of a study of the coronae of stars with active chromospheres [19] have shown that these stars are some 100 times more luminous than the Sun in soft X-rays. When their more rapid rotation and greater surface area are taken into account, RS CVn's may not be particularly unusual, but just an extreme case of normal stellar activity.

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DISCUSSION FOLLOWING WALTER, CHARLES AND BOWYER

Eaton: I have two points about your interpretation of the X-ray observations of UX Ari that I wish you would clarify. First, you have interpreted the sudden appearance of X-ray emission on 15 February 1978 as the emergence of an active region from behind the limb. This fixed the height of the emitting loop structures at $\sim 0.1\ R_{\star}$. How well does this interpretation agree with the optical light curve of UX Ari, i.e. is the light variation, presumably caused by spots, consistent with having no loops on the hemisphere seen on 14 Feburary 1978? Second, you presented observations obtained only ½ year earlier extending over nearly a complete rotational period of the binary which did not show significant variation in X-ray flux. Again, if you assume the spots giving rise to the optical light variation correspond to the feet of the coronal loops, is the lack of variation consistent with the optical light variation? What limits do you place on the extent of the corona in longitude at these two epochs?

Walter: First question: To the limits of our data we can't say there are no loops, but the number must be down by at least a factor of four. Due to the number of loops and the expected stability of the loops, it is extremely difficult to make enough disappear (and reappear) to explain the observation unless we postulate that they were indeed occulted by the body of the star. Since it happened during maximum light, when such an effect might be expected, it is very suggestive.

Second question: The earlier observation was centered near minimum light, and we scanned for five days, thus missing the phase of maximum light. Since the loops are optically thin, and since the corona is limb brightened, a corona covering 180° of longitude would be observable for nearly the entire period. Unfortunately we can't put good limits on the extent of the corona during the earlier observation because the aspect correction to the collimator response is large when the observed corona should be disappearing. The extent derived of $\sim 120^{\circ}$ of longitude covered by the bulk of the corona during the later observation is not inconsistent with earlier observations.

van 't Veer: The geometrical extension of the corona is limited by the Roche configuration of the system. Does this effect have to be taken into account for RS CVn stars?

Walter: I don't think so. For the most part the stars do not fill their Roche lobes and the derived coronal scale heights put the loops well inside the lobe. In the systems that may fill their Roche lobes, like RT Lac, this probably won't change things much because the magnetic flux tubes should be sufficiently rigid to keep the corona intact.

Feldman: Are there any bona fide RS CVn systems that definitely do not show X-ray emission, especially after observation by HEAO-2?

Walter: NO. Steve Shore has predicted that about 10% of them shouldn't be there, so it is getting interesting. The HEAO 1 A-2 upper limits are mainly greater than 10^{31}ergs^{-1} due to the large distances to these sources. Our first HEAO-2 IPC observations have shown nine new sources out of nine observed. This makes 24 definite detections, with one more possible. It has been suggested that Z Her is likely to be less active, but we haven't observed this yet.

Meyer: Since the thermal scale height of the 10^7K corona is more like a stellar radius in your case, the smaller extent of the corona must be due to the magnetic confinement in flux tubes which typically reach only out to 1/10 of the radius. This probably indicates that the characteristic separation of the two footprints of such flux tubes at the stellar surface is also only of this order of magnitude, which should then be the distance over which magnetic polarity at the surface changes.

Walter: In the case of UX Ari, we have calculated a loop length of 3×10^{10}cm, which is about one seventh the radius of the subgiant. Since the loop must be anchored to the surface, the footprints must indeed be separated by about .1 of the stellar radius and the height of the corona must also be of this order, as we have measured in UX Ari.