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X-RAY SPECTRA AND THE ROTATION-ACTIVITY CONNECTION OF RS CANUM VENATICORUM BINARIES

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ABSTRACT

Results are presented from a survey of RS CVn binaries which were observed with the imaging proportional counter (IPC) on board the *Einstein Observatory*. Spectral analyses of the IPC pulse height spectra show that the coronae of RS CVn binaries always contain hot gas with temperatures in excess of 10^7 K, similar to active late-type main-sequence stars, and that at least two temperature components are necessary to account for the higher quality IPC spectra (when absorption is unimportant). We argue that these bimodal temperature distributions found by the IPC are indicative of true distributions of emission measure versus temperature that are continuous (just as is the case for magnetically confined coronal plasma loops observed on the Sun). We further show that none of the derivable X-ray characteristics of RS CVn binaries depend on rotation period, implying that previous claims of period-activity relationships in RS CVn binaries were unfounded.

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

I. INTRODUCTION

RS CVn binaries are close binary systems normally consisting of an F-, G-, or K-type primary, orbited by a late G- or early K-type secondary, usually of luminosity class IV. Orbital periods lie between 0.5 and 14 days (with a rather ill defined upper limit); short-period systems rotate synchronously, and the mass ratios are normally of order unity. Typical defining characteristics of RS CVn binaries include the presence of Ca II H and K emission lines in their optical spectra and photometric variations in their integrated light curves, commonly attributed to starspots. However, as already pointed out by Hall (1976), not all the defining characteristics can be found in any one individual system, and in recent years the group of RS CVn binaries has been expanded to include objects which are similar to known RS CVn systems in only some aspects. Thus, RS CVn binaries have become a rather heterogeneous group of stars, whose properties have recently been reviewed by Hall (1976, 1981), Catalano (1983), Bopp (1983), and Charles (1983).

The strong (often variable) chromospheric line emission in Ca II H and K, Hα, and UV resonance lines has for many years been considered as a manifestation of powerful plasma heating mechanisms, which must operate at the stellar surface in all RS CVn systems at levels orders of magnitude above those found in "normal" main-sequence stars. RS CVn binaries were the first class of stellar (coronal) X-ray sources to be discovered: Using nonimaging detectors, Catura, Acton, and Johnson (1975) and Mewe *et al.* (1975) reported the detection of the nearby RS CVn system Capella in soft X-rays, and Walter *et al.* (1980) detected 15 of 59 RS CVn systems (known at the time and surveyed) using the *HEAO 1* observatory. Typical X-ray luminosities as reported by Walter *et al.* (1980) were in the range $3\text{–}40 \times 10^{30}$ ergs s^{-1}, and the low-resolution *HEAO 1* X-ray spectra were consistent with thermal bremsstrahlung emission from a solarlike plasma. These observational features led Walter *et al.* (1980) to propose the analog of a solar corona as the likely source of the observed X-ray emission. Using the *Einstein Observatory* imaging proportional counter (IPC; Gorenstein, Harnden, and Fabricant 1981), Walter and Bowyer (1981) carried out a survey of 39 RS CVn systems and detected all targets with characteristic X-ray luminosities in the range $10^{29}\text{–}10^{31}$ ergs s^{-1} in the passband 0.2–4 keV.

It is the purpose of this study to expand on the work of Walter and Bowyer (1981) by considering all the available IPC data in a uniform fashion, and in particular, by analyzing the available IPC pulse height (PH) spectra to study the properties of the coronae in RS CVn systems in more detail. The structure of our paper is as follows. In § II we describe the data used and the analysis performed; § III gives the results of our spectral analysis, as well as the results from a correlation analysis of all the known stellar parameters of the RS CVn systems under study. Our conclusions are given in § IV.

II. OBSERVATIONS AND DATA ANALYSIS

a) The Sample

Hall (1981) compiled a list of all RS CVn binaries known at that time (69 objects in total), containing short-period ($P < 1$ day), regular, and long-period ($P > 14$ days) systems. Of Hall's (1981) list, 56 systems were observed with the IPC (more than a dozen were also observed with other *Einstein Observatory* instruments),[1] and all but one were detected as soft X-ray sources.

Meaningful results in the analysis of IPC spectra of point sources can be obtained if the following requirements are met:

1. The source must lie in the central $4' \times 4'$ of the IPC

[1] HD 155555 was observed only by the objective-grating spectrometer (OGS; cf. Mewe *et al.* 1982); thus, 57 of the RS CVn binaries listed by Hall (1981) were observed by the *Einstein Observatory*.

field of view; thus only pointed targets can be used in practice. This restrictive condition arises because the precise in-flight determination of the spatial variations of the instrument gain is available only for this central region (Harnden *et al.* 1984; see this reference also for detailed information concerning the on-line IPC data analysis). The analysis of IPC spectra outside the central 4′ × 4′ region is hampered by a larger uncertainty of the instrumental gain.

2. The appropriate IPC data must be subjected to standard "REV 1" processing (Harnden *et al.* 1984) in order to derive the gain information needed for spectral analysis.

3. The source must be strong enough to provide a sufficient signal-to-noise ratio; we find this to be the case if there are at least 200 net counts in a 3′ circle centered on the source.

At the time of writing (1984 December), 27 stars from Hall's list met the above criteria; when the IPC reprocessing effort is completed, five additional sources (UX Ari, CQ Aur, AR Lac, ER Vul, and HD 5303) will meet the above selection criteria. In our sample we also included two "suspected" RS CVn systems not listed by Hall (1981) but classified as RS CVn by other authors: ξ Boo (by Basri, Laurent, and Walter 1983) and 39 Cet (by Boyd *et al.* 1983). Our full sample therefore consists of 29 RS CVn systems. Four systems (ζ And, σ Gem, V711 Tau, and HR 7275) have been observed more than once by the IPC. We have thus analyzed 34 fields altogether, and a log of our X-ray observations is given in Table 1.

TABLE 1

X-RAY OBSERVATIONS OF RS CVn's

Name	Pointing	Sequence Number	Counts	Exposure Time
λ And		3235	5067	1711
ζ And	2	3191	1075	1588
	1	3534	1682	3086
α Aur		849	8165	1288
ξ Boo		10418	1649	1706
54 Cam		5184	1132	4329
BH CVn		3213	5773	2589
39 Cet		3192	3023	1453
σ CrB		3219	5138	1717
AS Dra		3209	203	1735
DK Dra		3208	1309	1660
σ Gem	1	2310	3165	1545
	2	2311	5226	2519
Z Her		6970	2523	14689
V350 Lac		3231	237	1401
93 Leo		5190	716	2439
II Peg		3236	2824	1826
IM Peg		3233	1385	1829
SZ Psc		3234	3281	2706
V711 Tau	3	2306	7753	1529
(= HR 1099)	1	3152	73342	18766
	2	4496	8983	1523
TZ Tri		3533	670	1433
ξ UMa B		5189	2667	1893
HR 7275	1	3227	1556	1840
	2	4948	1643	1660
12 Cam		3196	384	1581
RZ Cnc		3204	331	2103
RS CVn		3211	1091	2286
AD Cap		3229	213	1494
RZ Eri		3195	501	4043
HK Lac		3230	296	706
RT Lac		3153	1940	16756
UV Psc		2300	410	1751

b) *The Optical Data*

Basic information for all the sample stars is presented in Table 2, where we give the name, HR/HD identification, spectral type, period, distance, and bolometric luminosity. Hall (1981) pointed out that only for the case of λ And do the photometric period and the orbital period differ by more than 1%. However, recently published extensive observations of 54 Cam (Eaton *et al.* 1981), 39 Cet (Eaton *et al.* 1983), and HR 7275 (Fried *et al.* 1983) reveal differences of about 9%, 36%, and 3% respectively. Therefore, for these four stars we have used the photometric periods, and for the remaining ones, the orbital periods from Hall's (1981) Table 1.

For 14 sample stars, trigonometric parallaxes measured with accuracy better than 35% (Hoffleit and Jaschek 1982; Jenkins 1952, 1963) are available, and we adopted the resulting distances. For another nine stars we took distances from Hall (1976), obtained from spectroscopic parallaxes. Finally, we calculated spectroscopic parallaxes for the remaining six stars, using m_v from Hoffleit and Jaschek (1982) and Hall (1981), M_v from Mihalas and Binney (1981), and assuming no interstellar absorption. To obtain the bolometric luminosity L_{bol}, we have calculated the distance-independent quantity L_{bol}/d^2 for all sample stars, using data from Basri, Laurent, and Walter (1983) and Walter and Bowyer (1981) and using bolometric corrections from Mihalas and Binney (1981). Clearly, the error in L_{bol} (and later L_x) introduced by the uncertainty in distance increases with increasing distance, since accurate trigonometric parallaxes are available only for the nearby stars. Furthermore, the more distant systems are generally fainter and hence usually have less well determined spectral types and luminosity classes. We therefore decided to divide the sample into two subsamples by separately considering nearby ($d \leq 90$ pc) and more distant RS CVn systems. The first subsample (19 stars) will be the basic subject of our analysis; the 10 more distant stars will be considered as a supplementary sample. The mean error of L_{bol} due to the errors in distance can be crudely estimated as being of the order of 45% for the *nearby* subsample.

c) *Analysis of the X-Ray Data*

In order to obtain IPC pulse height spectra, we considered the counts in a 3′ circle centered on the source and subtracted a local background determined from an annulus centered on the source with inner and outer radii of 5′ and 6′ respectively. For the fit we used all the PH channels with sufficient signal. In particular, we used the lowest energy PH channel, which has the smallest efficiency (~70%). We considered only thermal plasma spectra as computed by Raymond and Smith (1977) and Raymond (1980) for the emission of optically thin radiation from a plasma in collisional equilibrium; these spectra include continuum radiation (recombination, bremsstrahlung, two-photon continuum) as well as line radiation from the 12 most abundant elements.

For all observations of our sample stars, we fitted one- and two-component temperature models[2] to the observed PH

[2] We have not attempted to fit the X-ray spectra of RS CVn binaries with loop spectra. Although constraints on loop models can be derived from IPC spectra (see Schmitt 1984; Schmitt *et al.* 1985), we feel that such a procedure is physically unjustified in the present case. Standard loop models require the X-ray–emitting structures to be in hydrostatic equilibrium and exclude any variability on time scales shorter than the radiative cooling time scale. RS CVn binaries, however, often show rapid time variability (see, for example, Walter Gibson, and Basri 1983; Barstow 1984). Furthermore, the coronal topology in RS CVn binaries might be quite different from that observed in the Sun, with loops possibly interconnecting the two binary components (Walter, Gibson, and Basri 1983; Uchida and Sakurai 1983), so that the loop models derived in the solar context might be inappropriate for the modeling of coronal structure in RS CVn binaries.

TABLE 2

CHARACTERISTICS OF THE OBSERVED STARS

Star	HR	HD	Spectral type[a]	log P[a]	Distance[b] (pc)	log L_{bol} adopted	Notes
λ And	8961	222107	G7–8 IV–III	1.73	20.0	34.7	1
ζ And	215	4502	K1 II	1.25	27.0	35.0	
α Aur	1708	34029	G5 III + G0 III	2.02	12.5	35.6	
ξ Boo	5544	131156	G8 V + K5 V	1.02	6.41	33.3	2
54 Cam	3119	65626	G0 + G0	1.01	26.3	33.8	3
BH CVn	5110	118216	F2 IV + K IV	0.42	45.5	33.4	
39 Cet	373	7672	G5 III	1.89	66.7	35.0	4
σ CrB	6063	146361	F8 V + G IV	0.057	22.2	33.9	5
AS Dra	...	107760	G3 V + K0 V	0.73	31.2	33.1	6
σ Gem	2973	62044	K1 III	1.29	55.6	35.4	
Z Her	...	163930	F4 V–IV + K0 IV	0.60	85	34.1	7
V350 Lac	8575	213389	K2 IV–III	1.25	68	34.7	8
93 Leo	4527	102509	A7 V + G5 IV–IIIe	1.86	45.5	34.7	
II Peg	...	224085	K2–3 V–IV	0.83	29.4	33.6	6
IM Peg	8703	216489	K1 IV–IIIp	1.39	50	34.8	8, 9
V711 Tau	1099	22468	K0 IV + G5 V	0.453	31.2	34.1	10
TZ Tri	642	13480	G5 III + G5 III	1.17	75	35.3	8
ξ UMa B	4374	98230	G0 V	0.60	7.30	33.3	
HR 7275	7275	179094	K1 IV–III	1.44	35	34.4	8, 9, 11
DK Dra	4665	106677	K0 III + K0 III	1.81	95	35.3	8
SZ Psc	...	219113	K1 IV–V + F8 V	0.60	100	34.5	7
12 Cam	1623	32357	K0 III	1.90	134	35.6	8
RZ Cnc	...	73343	K1 III + K3–4 III	1.34	310	35.1	7
RS CVn	...	114519	F4 IV–V + K0 IV	0.68	145	34.2	7
AD Cap	...	206046	G5 + G5	0.47	250	34.7	7
RZ Eri	...	30050	A5–F5 V + sg G8	1.59	105	34.6	7
HK Lac	...	209813	K0 III + F IV	1.40	150	35.3	7
RT Lac	...	209318	G9 IV + K1 IV	0.71	205	34.3	7
UV Psc	...	7700	G2 V–IV + K0 IV	−0.065	125	34.1	7

NOTES.—(1) Spectral type and period from Boyd *et al.* 1983. (2) ξ Boo, suspected, data from Basri, Laurent, and Walter 1983. (3) Period from Eaton *et al.* 1981. (4) AY Cet, suspected, data from Eaton *et al.* 1983. (5) Spectral type from Agrawal, Riegler, and White 1981. (6) Distance from Jenkins 1952, 1963. (7) Distance from Hall 1976. (8) Distance calculated using $M(_v)$ from Mihalas and Binney 1981, V from Hall 1981, no interstellar absorption assumed. (9) Spectral type from Herbst 1973. (10) Spectral type and period from Bartolini *et al.* 1983. (11) Period from Fried *et al.* 1982.

[a] From Hall 1981 unless otherwise noted.

[b] From Hoffleit and Jaschek 1982 unless otherwise noted; an arbitrary distinction between "nearby" and "more distant" stars has been set at 90 pc.

spectra. Each component was determined by two parameters, the temperature and a normalization constant from which the emission measure $n_e^2 V$ was computed; we therefore obtained for the one-component models the temperature T_{one} and the emission measure EM_{one}, and for the two-component models the two temperatures T_{low} and T_{high} and the corresponding emission measures EM_{low} and EM_{high}. The best-fit parameters were determined by finding the global minimum of the χ^2 test statistic. During the minimization procedure, we allowed both components to vary freely and independently, rather than fixing a particular component at some value or letting only one component vary at a time; this is important for a correct interpretation of the obtained fit parameters, as we shall see below. We considered only the X-ray temperatures as "interesting" parameters in the sense described by Avni (1976); this procedure results in tighter constraints on the derived temperatures, with no errors derived for the inferred emission measures. It should be emphasized that the one- and two-component models considered by us serve merely as a convenient mathematical description of X-ray spectra, rather than as a physically consistent description of the X-ray emitting gas in the coronae of RS CVn binaries.

For a few of the more distant stars in our sample, a considerable improvement in the quality of the fit was achieved by assuming a nonzero value of the hydrogen column density N_H of the intervening interstellar medium. For most of the nearby stars, the best-fit values of N_H do not exceed 10^{19} cm^{-2}, in agreement with values for the interstellar hydrogen density derived by Paresce (1984); the largest column density we obtained for our sample stars is that for V350 Lac: $N_H = 2.0 \times 10^{20}$ cm^{-2}, which corresponds to an optical extinction of $A_v \approx 0.1$ mag (Gorenstein and Tucker 1976). Thus, our assumption that $A_v = 0.0$ for calculation of spectroscopic parallaxes seems to be well warranted.

We did not attempt to use model spectra with different metal abundances in order to obtain better fits. The modest energy resolution of the IPC (100% at 1 keV) does not allow us to see any spectral lines or edges which could be used to measure the relative abundances of particular elements, and we cannot assert whether a better fit indicates real abundance differences or is a fortuitous improvement through the introduction of additional fit parameters. Furthermore, the high-resolution spectroscopy of RS CVn binaries performed with the *Einstein Observatory* solid state spectrometer (SSS; see Swank *et al.* 1981, and references therein) has shown that for all but one system (α Aur = Capella) in that sample (five of which are included in our sample), the abundances of Mg, Si, S, and Fe are within a factor of 2 of solar values, and that the solar

TABLE 3

RESULTS FOR SINGLE-TEMPERATURE FITS

Name	Pointing	Confidence Level (%)	log T	68% Confidence Interval in log T	EM/D^2 (10^{50} cm^{-3} pc^{-2})	L_x/D^2 (10^{27} ergs s^{-1} pc^{-2})
ζ And	1	48	7.14	7.10–7.17	0.69	1.4
	2	88	7.08	7.04–7.11	0.70	1.6
54 Cam		93	7.25	7.20–7.33	0.40	0.65
BH CVn		75	7.27	7.24–7.31	3.6	5.6
39 Cet		32	7.66	7.57–7.75	4.5	5.9
AS Dra		84	7.25	7.12–7.53	0.17	0.27
σ Gem		41	7.16	7.14–7.18	3.1	5.7
		77	7.19	7.16–7.21	2.7	4.8
Z Her		52	7.17	7.14–7.20	0.25	0.47
V350 Lac		37	7.38	7.22–7.64	0.40	0.58
93 Leo		95	6.92	6.87–6.98	0.22	0.63
II Peg		71	7.42	7.35–7.49	2.9	4.0
IM Peg		66	7.23	7.19–7.27	1.4	2.3
V711 Tau	3	82	7.31	7.28–7.35	8.6	13
	2	81	7.34	7.31–7.37	11	16
TZ Tri		31	7.14	7.09–7.19	0.61	1.2
HR 7275	1	97	7.19	7.14–7.25	1.1	2.0
	2	76	7.22	7.18–7.27	1.5	2.5
DK Dra		25	7.27	7.21–7.35	1.3	2.0
SZ Psc		86	7.52	7.44–7.58	2.8	3.8
12 Cam		24	7.44	7.27–7.68	0.57	0.80
RZ Cnc		64	7.43	7.28–7.66	0.39	0.54
RS CVn		42	7.66	7.50–7.80	1.0	1.4
AD Cap		42	7.18	7.07–7.36	0.23	0.42
RZ Eri		81	7.37	7.26–7.52	0.38	0.54
WK Lac		68	7.75	7.45–8.08	0.95	1.2
RT Lac		6	7.51	7.42–7.61	0.35	0.49
UV Psc		6	7.10	7.03–7.18	0.25	0.55

abundances are in most cases included within the 90% confidence limits.

In order to determine whether a one- or two-component model is required for an accurate description of the observed X-ray spectra, we adopt the null hypothesis that the observed X-ray spectrum is generated by the assumed model and test it by computing the confidence level which allows us to reject this null hypothesis. In six cases (listed in Table 4), we found that the one-component model was not acceptable at the greater than 99% confidence level, and a two-component model was required to obtain satisfactory fits.[3] An F-test was applied to these stars, which indicates preference for the two-temperature model with confidence levels greater than 90% in all cases, as seen in Table 4.

The best-fit spectral parameters for all sample stars are presented in Tables 3 and 4, referring to "one-temperature" and "two-temperature" objects respectively. The listed uncertainties in fit temperature represent 1 σ errors. The last column in each table contains the X-ray luminosity in the passband 0.15–4.5 keV, calculated by integration of the best fit intrinsic spectrum.

III. RESULTS AND DISCUSSION

The following discussion is focused on two questions: First, what can we learn about the distribution of emission measure as a function of temperature from the fitted spectral parameters? Second, are X-ray parameters such as T, EM, and L_x in fact correlated with other stellar parameters, such as $L_{\rm bol}$ or photometric period, in the context of the so-called "rotation-activity connection" for late-type stars?

a) The Distribution of Coronal Temperatures

As already mentioned, the X-ray spectra of most survey stars (i.e., 15 of 19 nearby systems and all the more distant systems) can be fitted by a single-temperature model with essentially no interstellar absorption. An example is the X-ray spectrum of RS CVn itself (see Fig. 1*a*; observed source counts [*circles*] are plotted together with the counts predicted from the best fit [*stepped curve*]). However, about one-third of nearby RS CVn binaries (six of 19) do require a two-temperature model. An example of such a two-component X-ray spectrum is that of V711 Tau (HR 1099), displayed in Figure 1*b*. Although the latter spectrum contains ~70,000 counts, it can be adequately fitted by a two-temperature component model (reduced $\chi^2 = 0.9$) if the systematic errors (assumed to be ~3% of the total number of counts in each channel) are taken into account; we can with certainty exclude a single-component model. (We note here that definitive fits such as these can only be obtained by using the "gain histogram," as discussed by Harnden and Fabricant 1985; the use of a single mean gain value is not adequate.)

Although the determination of coronal temperature does not intrinsically depend on distance, it is nevertheless useful to distinguish between nearby and more distant stars in this context. Since the X-ray luminosities of most RS CVn binaries (cf. Tables 3 and 4) scatter only over a range of about one order of magnitude, the total number of collected source counts and hence the quality of the observed PH spectrum depend primarily on the distance of the object and the exposure time. The

[3] The confidence level for the acceptance of a two-temperature model fit for α Aur (3%) is small because systematic errors were not taken into account; however, the spectrum of α Aur contains ~8000 counts, and if systematic errors are taken into account (see below), the confidence level for acceptance becomes much higher (~10%).

TABLE 4

RESULTS FOR TWO-TEMPERATURE FITS

Name	Confidence level (%)	F-test Confidence level	log T_{low}	68% Confidence Interval in log T	log T_{high}	68% Confidence Interval in log T	EM_{low}/D^2 (10^{50} cm^{-3} pc^{-2})	EM_{high}/D^2 (10^{50} cm^{-3} pc^{-2})	L_x(low)/D^2 (10^{-27} ergs s^{-1} pc^{-2})	L_x(high)/D^2 (10^{27} ergs s^{-1} pc^{-2})
λ And	38	98.3	6.40	6.36–6.52	7.20	7.16–7.26	0.32	3.7	0.97	7.2
α Aur	97	91.9	6.35	6.19–6.44	6.85	6.83–6.97	0.64	4.4	2.0	12.4
ξ Boo	69	99.6	6.35	.6.31–6.40	7.10	7.06–7.37	0.32	0.51	1.0	1.2
σ CrB	68	93.3	6.50	6.38–6.60	7.14	7.10–7.19	0.40	3.0	1.1	6.5
ξ UMa B	77	99.8	6.35	6.28–6.39	7.05	6.98–7.09	0.59	8.5	1.8	2.3
V711 Tau[a]	45	99.9	6.45	6.42–6.51	7.40	7.37–7.54	0.66	6.0	1.9	8.7

[a] First pointing.

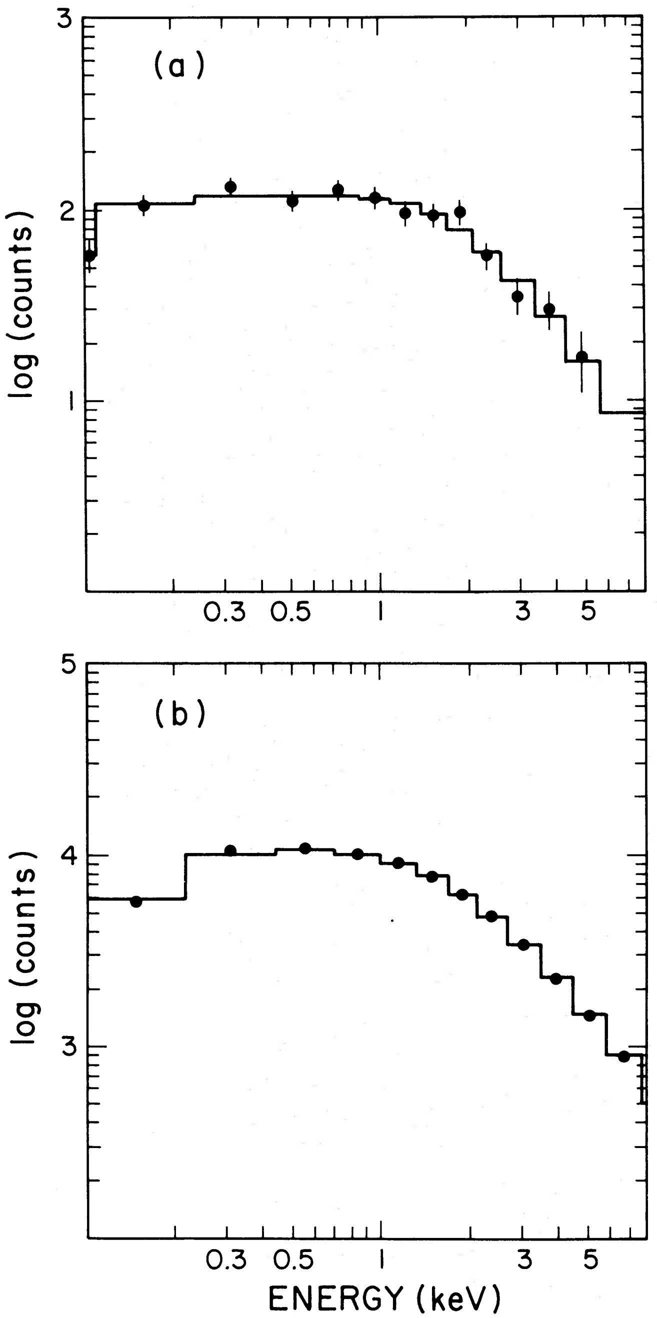

FIG. 1.—IPC spectrum (*circles*) together with best-fit predicted spectrum (*stepped curve*) of (*a*) RS CVn and (*b*) V711 Tau.

effective exposure times for all but three of the analyzed images are clustered around $\sim 2020 \pm 740$ s, i.e., a typical viewing time during one satellite orbit; hence we expect a negative correlation between the distance of a source and the number of counts in its image, which is clearly present in our data (see Fig. 2; note that V711 Tau is not plotted). Only two of the more distant systems (RS CVn, RT Lac) have more than 500 net source photons in a standard circle; hence the statistical errors and the errors in derived best-fit parameters become quite large.

The distribution of the derived coronal temperatures of the RS CVn binaries is shown in Figure 3. In Figure 3*a* we show the distribution of $T_{\rm low}$ and $T_{\rm high}$ for six two-component systems (the five nearest systems plus V711 Tau), followed in Figure 3*b* by the histogram of $T_{\rm one}$ for the remaining nearby stars and more distant objects; in Figure 3*c* we show the two-component distribution of coronal temperatures obtained from the IPC spectra of 26 late-type dwarfs (spectral types G–M, luminosity classes IV–V; Majer *et al.* 1984). It is important to note that all the two-temperature model fits shown in Figure 3 were derived from spectra with more than 1500 counts (ranging from about 1500 to more than 8000 counts) for objects with distances in the range between 6.5 (for ξ Boo) and 22 pc (for σ CrB), and that II Peg is the nearest RS CVn system with sufficient count statistics for which we do not require a two-temperature component model.

From Figure 3 we reach the following conclusions: First, the distribution of $T_{\rm low}$ and $T_{\rm high}$ for the nearest RS CVn's is very similar to that of late-type dwarfs; we note in this context that all the dwarf stars shown in Figure 3*c* lie within 15 pc, and that the best two-component fits to their spectra require no absorbing hydrogen column density (Majer *et al.* 1984). Second, the single-temperature values which give acceptable fits to more distant RS CVn's correspond to the high-temperature component, seen in the two-component fits of the nearby objects. Combining this result with the discussion of Figure 2 presented above, it becomes clear that the fact that a $T_{\rm low}$ component is not necessary for fitting spectra of more distant stars is due to that component's absorption by intervening interstellar material. Hence we conclude from the IPC spectra that coronae of RS CVn's are not isothermal, and we assert that the spectrum of any RS CVn binary would require at least a bimodal distribution of emission measure as a function of temperature, provided interstellar absorption were not present (and of course provided the spectrum were of sufficient statistical precision).

It is instructive to compare our results to those obtained with the *Einstein Observatory* SSS for RS CVn binaries. In Figure 4, we can compare the distribution of $T_{\rm low}$ and $T_{\rm high}$ of the nearest stars from our sample (cf. Fig. 3*a*) with the temperature distribution found by Swank *et al.* (1981). This comparison shows the complementary character of both distributions, i.e., the SSS low-temperature components fill the gap in the differential emission measure distribution between log $T \approx 6.6$ and 7.0 observed by the IPC, and the SSS high-temperature components cover the region above that corresponding IPC temperature component up to log $T \approx 8.0$. Furthermore, the temperatures found with the IPC and SSS are statistically significantly different for the 5 RS CVn binaries (λ And, α Aur, σ CrB, V711 Tau, and RS CVn) which were observed by both instruments (Fig. 5). For each star, the two SSS temperatures (*upper row*) and two or one IPC temperatures (*lower row*) are plotted together with their 2 σ error bars. In all cases, the IPC and SSS low-temperature components are well separated. For α Aur[4] and RS CVn, the high-temperature component found in the IPC lies within 2 σ of the SSS $T_{\rm high}$ component, but note that the OGS result for α Aur does lie outside the IPC error bar. Such discrepancies cannot be due to instrumental calibration effects: Harnden and Fabricant (1985) have demonstrated that the IPC and SSS give good agreement for the fitted spectral parameters of sources for which a simple, plausible model is known. Rather, we take this

[4] Capella (α Aur) was also observed with the *Einstein* OGS (Mewe *et al.* 1982), and those results are plotted in Fig. 5 as well.

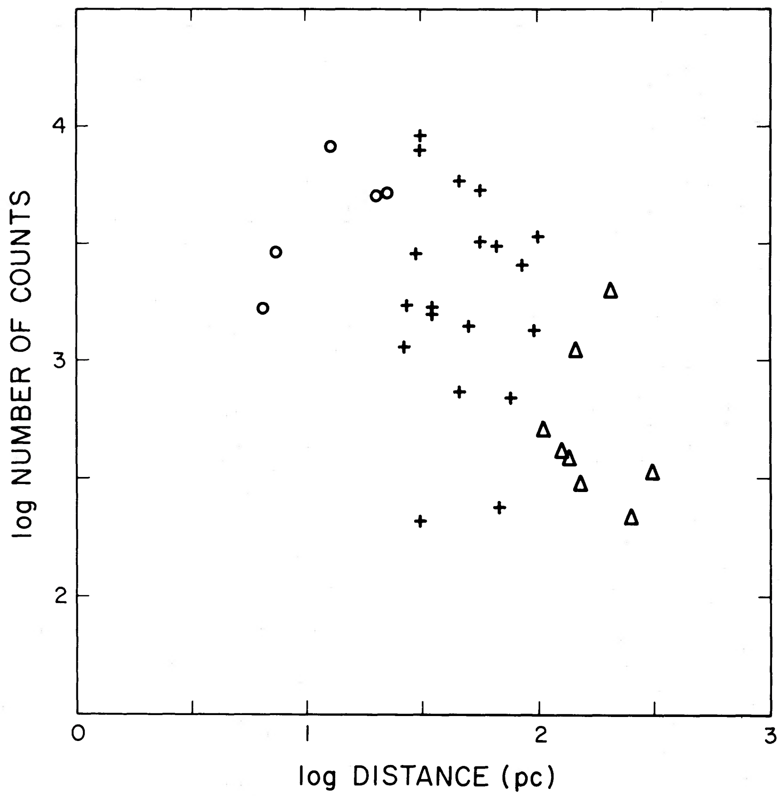

FIG. 2.—Number of counts collected vs. distance for the sample stars (V711 excepted): *circles*, stars which require two-component spectra; *triangles*, more distant systems; *plusses*, single-component systems.

disagreement as an indication of the inadequacy of the assumed intrinsic spectral model. Therefore, although a bimodal distribution of emission measure is a (mathematically) sufficient description for either the IPC or the SSS data considered alone, it is not an adequate description of all the available data from both instruments.

The conclusion that four temperature components must necessarily exist in the coronae of RS CVn binaries seems to us, however, premature. First, the energy bands covered, as well as the effective areas, are different for two instruments (0.2–4.0 keV for IPC vs. 0.4–4.0 keV for SSS); these distinctions may contribute to the differences in the derived spectral parameters, especially those of the cooler component. Second, the better energy resolution of the SSS (~ 160 eV through the entire energy range) provides much tighter constraints on the permissible temperatures of the cooler component, whereas in the case of IPC the uncertainties of both temperatures are comparable (cf. Fig. 5). Third, there might be systematic differences in the assumed spectra as well as systematic errors in the instrumental response and the resulting fitting procedures. The total number of components necessary to describe both the IPC and the SSS spectra simultaneously is thus uncertain; however, our basic conclusion that more than two components are necessary to account for the observed X-ray spectra remains valid.

We instead propose that the actual distribution of emission measure versus temperature in RS CVn binaries is continuous, and that the different "components" identified in the observed X-ray spectra should not necessarily be considered as physically distinct entities, but rather as manifestations of a continuous emission measure distribution, which is observed with limited spatial and spectral resolution. Mewe *et al.* (1982) reached a similar conclusion for α Aur from their OGS analysis of that star. In the case of the Sun, the X-ray emitting gas is magnetically confined in loops which are known to contain emission measure at a variety of temperatures (cf. Vaiana and Rosner 1978). If the solar analog for RS CVn binaries is indeed correct (Walter *et al.* 1980), we might expect the X-ray emitting gas in RS CVn binaries to be magnetically confined and to be characterized by a continuous emission measure distribution.[5]

b) *Period-Activity Relationships*

Much effort has been devoted to the task of finding predictors for stellar activity. From the study of the Ca II chromospheric activity indicators it had become clear, well before the beginnings of stellar X-ray astronomy, that rotation had an important role to play in the determination of the observed activity levels (Kraft 1967). That Walter and Bowyer (1981)

[5] This view is supported by calculations of Schmitt (1984), who showed that two-component models inevitably yield good fits when the X-ray spectrum emitted from a magnetically confined loop—as seen in an instrument like the IPC—is fitted with isothermal temperature components as long as the temperature at the loop apex is above the carbon edge ($\log T \approx 6.5$); the two components are simply required to account for the emission in the two independent spectral windows of the IPC (centered at ~ 0.2 and ~ 2.0 keV) which lie on either side of the carbon edge. Although the spectral resolution of the SSS (and hence the number of its independent spectral windows) is much higher than that of the IPC, the inversion problem (i.e., the direct determination of the run of emission measure vs. temperature) is ill conditioned because of the very nature of the functional variation of the input spectra with temperature (Craig and Brown 1976). Therefore a relatively small number of components is sufficient to describe the synthesized spectrum of any chosen thermal input spectrum, a fact that remains true no matter what the spectral resolution of the detector.

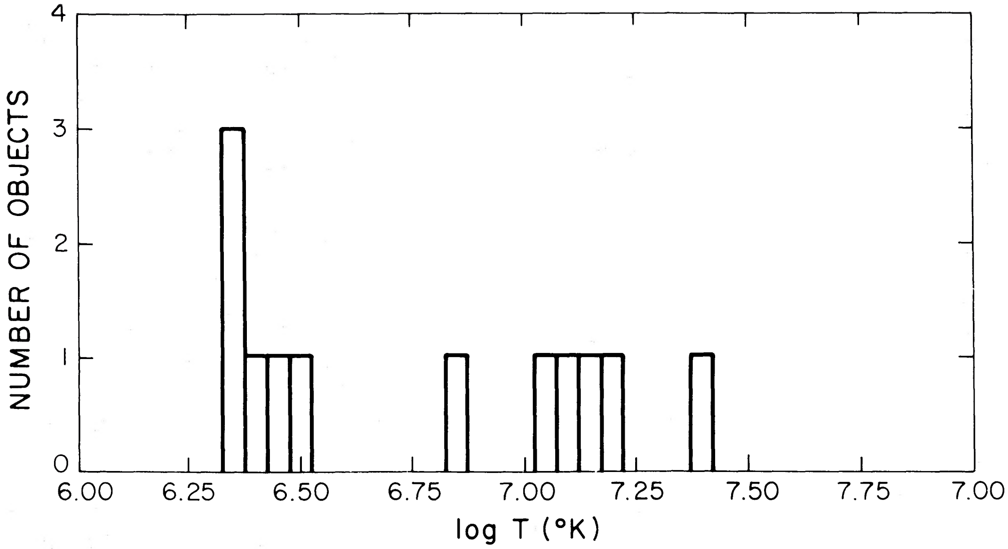

FIG. 3*a*

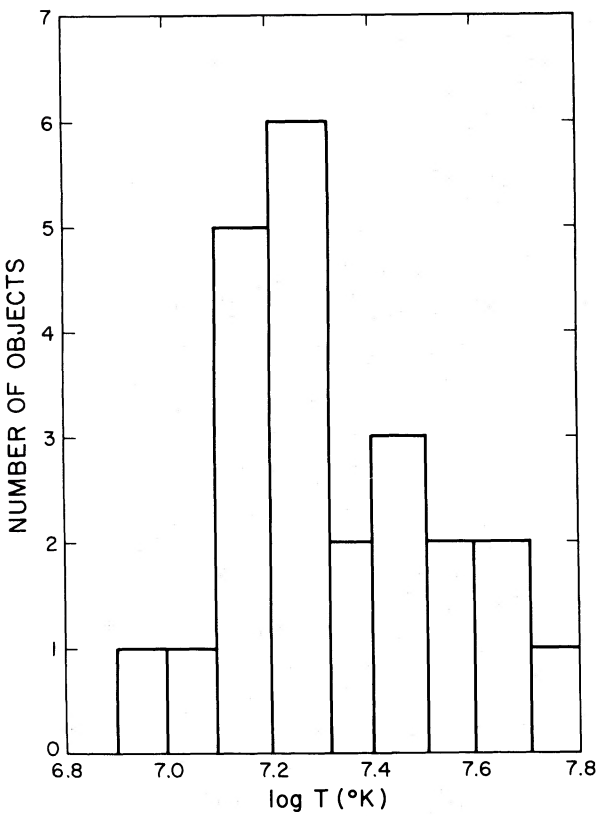

FIG. 3*b*

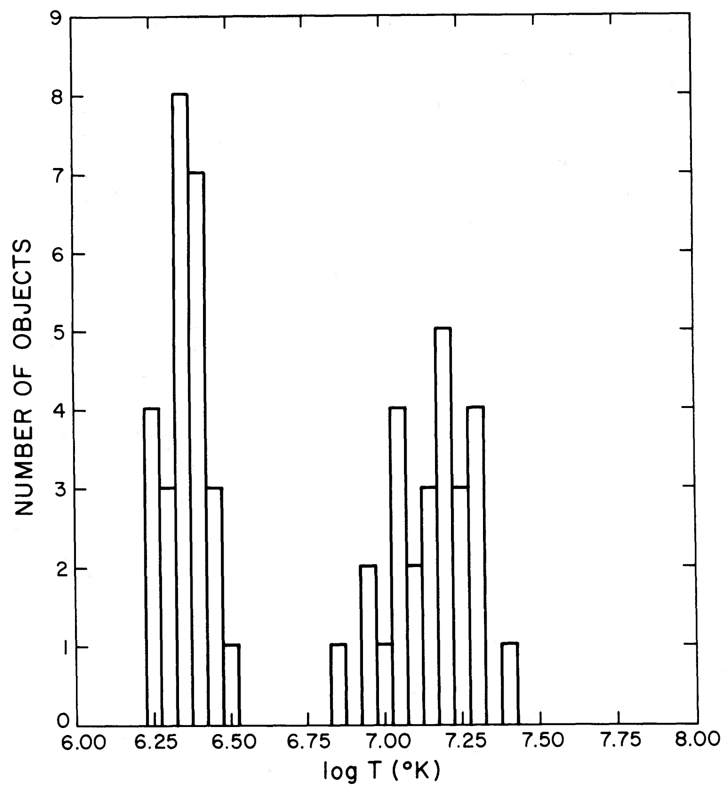

FIG. 3*c*

FIG. 3.—Temperature distribution histogram for (*a*) the six two-component systems, (*b*) 23 single-component systems, and (*c*) sample of 26 late-type dwarf stars from Majer *et al.* (1984).

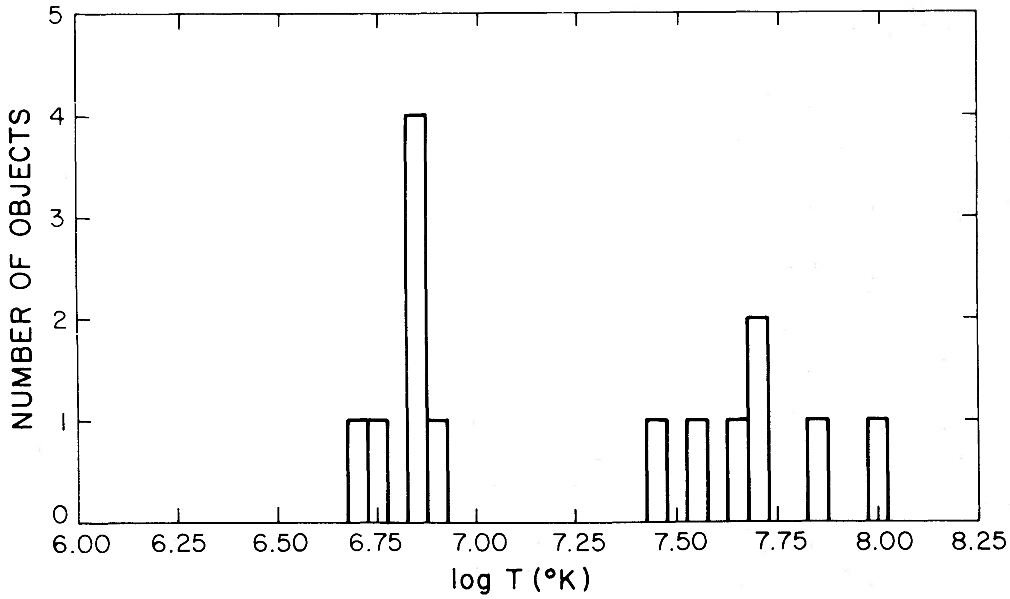

FIG. 4.—Temperature distribution histogram for 7 RS CVn binaries observed with SSS by Swank *et al.* (1981)

found a correlation between the ratio of X-ray and bolometric luminosity of RS CVn binaries and their rotation period (of the form $L_x/L_{bol} \approx P^{-1.2}$), which they interpreted in the framework of dynamo mechanisms thought to be ultimately responsible for the observed X-ray emission, was therefore a gratifying, but widely anticipated, result.

The current analysis demonstrates that the rotation-activity connection for RS CVn binaries is far more complex than previously thought. A hint of this complexity was found by Pallavicini *et al.* (1981), who derived—for late-type main-sequence stars and giants—a relationship between X-ray luminosity and equatorial rotation velocity $v \sin i$ of the form $L_x \approx (v \sin i)^2$ but noted that for the subgroup of RS CVn binaries L_x seemed to be independent of rotation velocity or period. Subsequently, Rengarajan and Verma (1983) showed that the correlation between L_x/L_{bol} and P found by Walter and Bowyer (1981) is mostly due to a dependence of bolometric luminosity on period, which can be simply understood from Kepler's third law: For longer period systems, the separation between the binary components becomes larger, and bigger stars can be accommodated in the system without mass exchange; these stars will have—for a given spectral type—

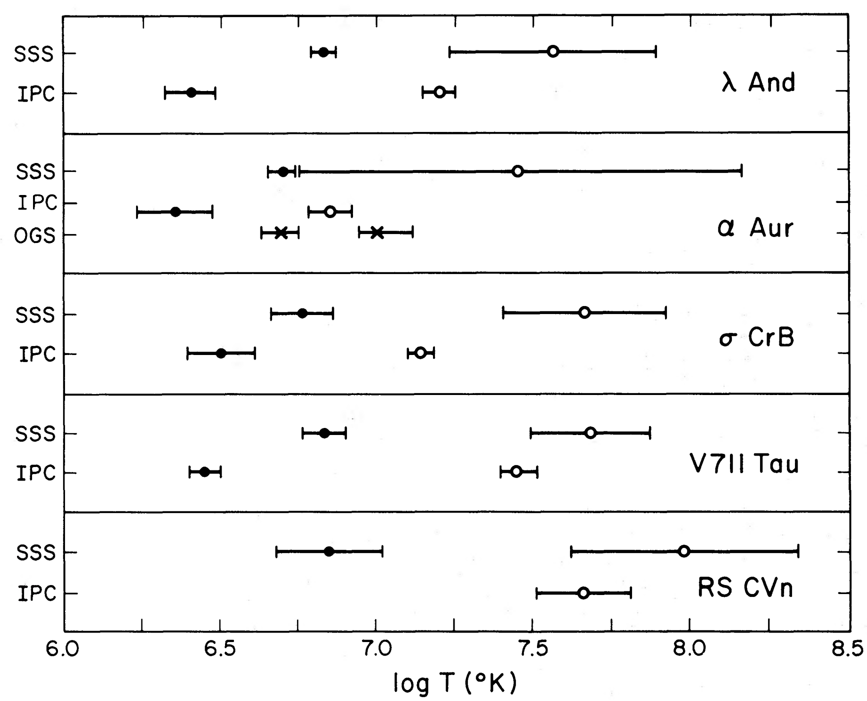

FIG. 5.—Comparison of X-ray temperatures determined by both the SSS (*upper values*; Swank *et al.* 1981) and IPC (*lower values*); horizontal bars denote 95% confidence level intervals. In the case of α Aur, the OGS result (Mewe *et al.* 1982) is also indicated with a cross.

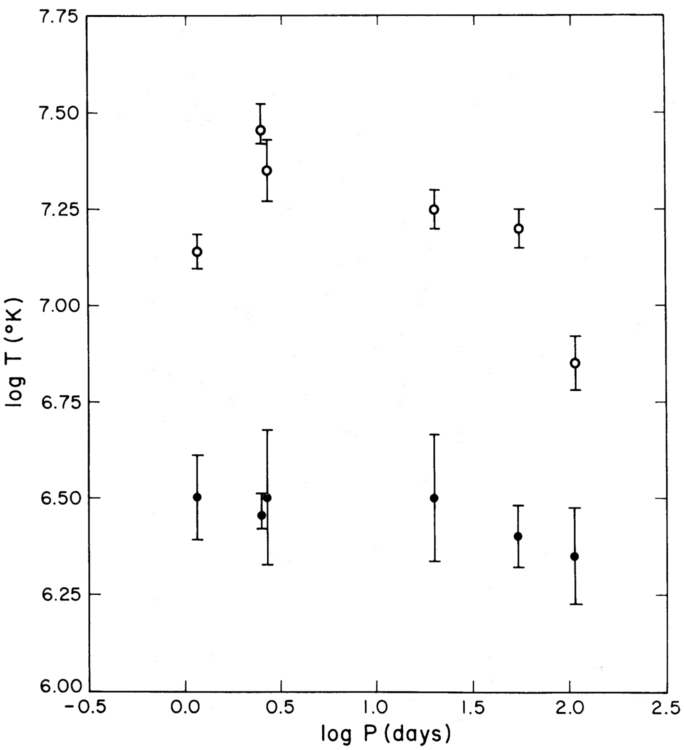

FIG. 6.—Fitted X-ray temperatures (*open circles*, high temperature; *filled circles*, low temperature) vs. period for systems which require two-temperature fits.

larger bolometric luminosities. To quantify this, let us assume that all systems have the same masses and the same ratio of stellar radius to binary separation; under these idealized circumstances we obtain $L_{\rm bol} \approx P^{4/3}$. Hence if L_x happens to be constant for all systems, we would expect $L_x/L_{\rm bol} \approx P^{-4/3}$, which is quite close to that found by Walter and Bowyer (1981).

In the following we shall show that for our sample of RS CVn binaries all X-ray properties, i.e., temperature, emission measure, and consequently X-ray luminosity, are indeed independent of period. This claim is substantiated by Figures 6 and 7, where we plot X-ray temperature versus period for both the two- and the one-component systems; in both cases the data are consistent with the hypothesis that X-ray temperature is independent of period. In order to find correlations of X-ray luminosity with variables other than period, we subjected the data for 28 stars for which we could derive X-ray luminosity, bolometric luminosity, period, and stellar radius R (i.e., the radius of the active component) to a common factor analysis for these parameters; the data are shown in Figure 8, where we plot L_x, $L_{\rm bol}$, and R versus P for all the sample stars which were used in the common factor analysis.

Common factor analysis is a classic statistical tool to find and identify the minimum number of independent variables in a given data set; an extensive description and discussion of the method can be found in the treatise by Kendall and Stuart (1976). We use normalized logarithmic variables, i.e., variables with zero mean and scaled by their respective dispersion, as recommended by Kendall and Stuart (1976), and then proceed to compute the correlation matrix for the above-mentioned variables.

Because the correlation matrix is positive definite and symmetric, it has real and positive eigenvalues, and our first task is

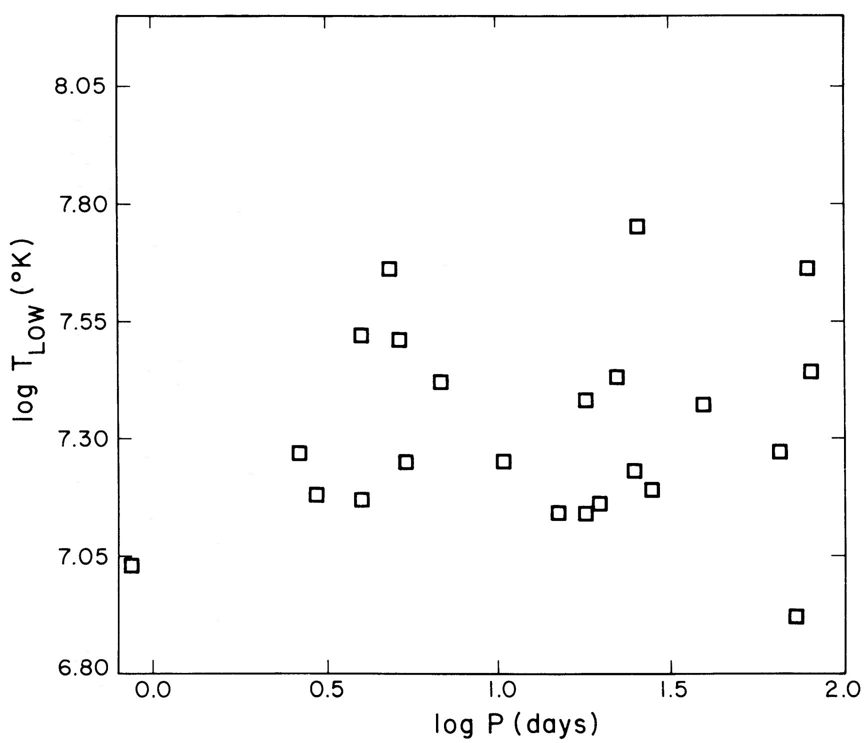

FIG. 7.—X-ray temperature vs. period for systems with acceptable one-temperature fits

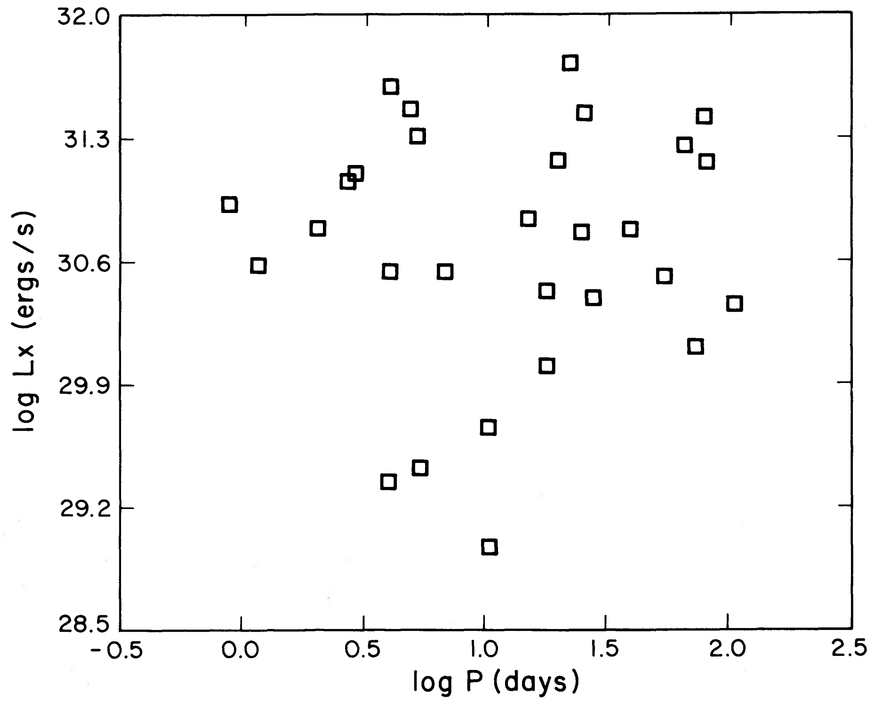

FIG. 8a

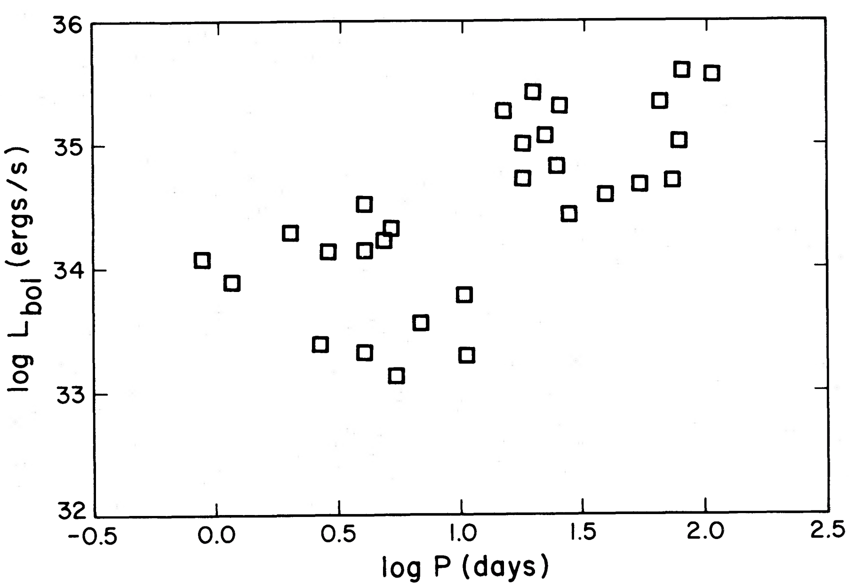

FIG. 8b

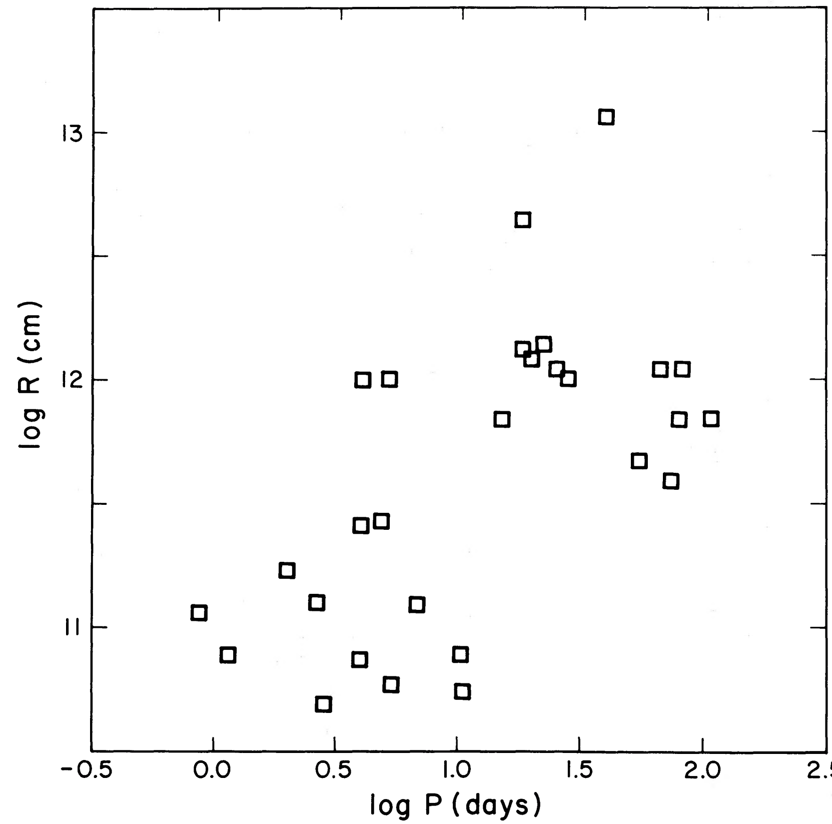

FIG. 8c

FIG. 8.—(a) X-ray luminosity vs. period for total sample (29 objects); (b) bolometric luminosity vs. period for total sample; (c) radius of active component vs. period for total sample.

to identify the significant eigenvalues. We find 90% of the variance in two eigenvalues and their respective eigenvectors. If we include the third-largest eigenvalue, the total variance increases by only 7%, and hence we will assume that only two significant eigenvalues (and corresponding eigenvectors) exist, i.e., we assume that the given data set (L_x, L_{bol}, R, and P) can be statistically described by two orthogonal uncorrelated linear combinations of the (original) physical variables. One of these uncorrelated variables is composed (at high significance level) only of contributions from L_x and P, whereas the other is composed of contributions from all the physical variables.

We next project the physical variables onto the subspace spanned by these two eigenvectors, normalize, and compute the correlation matrix of the normalized projected observable variables. We then find an extremely high correlation coefficient r between the projected bolometric luminosity and the stellar radius ($r > 0.99$). This correlation can be easily explained: since $L_{bol} \approx T_{eff}^4 R^2$ and T_{eff} changes relatively little for the sample stars, a natural correlation between L_{bol} and R results (as is observed), and hence projected radius and projected bolometric luminosity are entirely equivalent. Next, we consider the correlation between projected L_{bol} and projected period ($r = 0.75$) (or, equivalently, between projected radius and projected period with $r = 0.79$). The large correlation coefficient indicates that bolometric luminosity and period are not independent; this is precisely the claim made by Rengarajan and Verma (1983), whose physical interpretation we have already discussed above. Thus, out of the set of three variables L_{bol}, P, and R, there is only one variable (or possibly a suitable linear combination thereof) which is independent; this conclusion is strengthened by a common factor analysis applied just to these variables for our sample stars. We find almost 80% of the total variance in one variable and that the variances in the remaining two variables are equal.

Our analysis also shows that the projected X-ray luminosity is not correlated with the projected period ($r = 0.02$, before projection $r = 0.06$) and that it can only be correlated with the projected bolometric luminosity and radius ($r = 0.67$ and $r = 0.63$ respectively, before projection $r = 0.55$ and $r = 0.43$ respectively; we note that the similar correlation coefficients are clearly a result of the extremely high correlation between L_{bol} and R). In order to show the power of common factor analysis, we have plotted in Figure 9 the normalized radii versus normalized X-ray luminosities before (Fig. 9*a*; $r = 0.45$) and after projection (Fig. 9*b*; $r = 0.63$); the increase in correlation by projection is clearly visible. We stress that we could have equivalently picked bolometric luminosity rather than the stellar radius, but not the period. We wish to note in this context that L_x is correlated with rotation *velocity*, but as is obvious, since L_x and period are uncorrelated, this dependence *must* be caused by a correlation between L_x and R.

We thus arrive at the following physical picture: L_x is definitely uncorrelated with rotation period and, among the variables considered, is only correlated with R, the radius of the active component, or equivalently, the bolometric luminosity. If so, it is clear that the X-ray emission measure is correlated with R; because of the similar X-ray temperatures we find for the RS CVn binaries, the X-ray luminosity scales directly with the emission measure, with little scatter introduced by variations in temperature.

It is tempting to try to interpret the exponent connecting X-ray luminosity and radius of the active component (we find $\log R \approx [0.37 \pm 0.1] \log L_x$); however, because of the large uncertainties, we cannot distinguish between the case $L_x \approx R^2$ (in which case the bulk of the emission would come from loops near the surface of the star), and $L_x \approx R^3$ (in which case the emission would predominantly come from loops with a scale height of at least a stellar radius). Evidence for an extended corona in the case of the eclipsing RS CVn binary AR Lac was given by Walter, Gibson, and Basri (1983), with the extended corona providing about one-tenth of the total emission measure; however, White *et al.* (1984) dispute the conclusions reached by Walter, Gibson, and Basri (1983), and this issue therefore remains unresolved at the moment.

IV. SUMMARY AND CONCLUSIONS

We have shown that typical coronal temperatures in RS CVn binaries are in excess of 10^7 K very similar to temperatures found in other late-type stars (Schmitt 1984; Majer *et al.* 1984); this is not to say that there is no gas with even higher temperatures present, but if such gas is present, its emission measure must be small. Unless coronal material is continuously replenished, it must be confined, because the plasma temperature is of the order of the "gravitational" escape temperature; an obvious confining agent would be a coronal magnetic field, just as is the case for the Sun. If this is so, the emission measure would be expected to be a continuous function of temperature, which would provide a natural explanation for the multitude of temperature "components" seen by the *Einstein Observatory* SSS, IPC, and OGS and by the *EXOSAT* (Schrijver 1984) instruments. We therefore conclude that the observed X-ray spectra are consistent with spectra expected from coronal material.

We do not find any dependence of X-ray temperature, emission measure, or X-ray luminosity on rotation period, in contrast to the correlations found for late-type main-sequence and giant stars. Out of the four variables L_x, L_{bol}, P, and R which we considered, L_x can only be correlated with R, the radius of the active component. Equivalently, L_x can be correlated with L_{bol}; this is not surprising, since we find that L_{bol} and R are highly correlated, as is expected for a class of stars within a narrow spectral range. If the physical conditions in the coronae of RS CVn binaries are similar, i.e., if the temperatures are similar (which is the case observationally) and if the particle densities are the same (which we cannot establish observationally as yet), then the observed spread in activity (viz., in X-ray luminosity) can be interpreted as simply due to a variation in the volume available to X-ray–emitting coronal gas (viz., a variation in the number of "active regions").

Finally, why do the X-ray properties of RS CVn binaries not depend on period, surface rotation velocity, etc., as is the case for late-type main-sequence and giant stars? To some extent, the RS CVn stars are reminders that present-day theories for magnetic and coronal activity are not truly predictive and that the "agreement" between the relatively primitive theoretical expectations from such theories (viz., that activity ought to depend on Rossby number; Durney and Latour 1978) and observations of late-type main sequence stars (viz., Noyes *et al.* 1984; Schmitt *et al.* 1985) is in a deep sense fortuitous. RS CVn stars are not likely to have simply structured flows in their convection zones (primarily because tidal coupling is an important consideration), and therefore it is not a straightforward matter to predict the sense of any "rotation-activity" connection. For this reason alone, our result cannot be called surprising. A point worth noting, however, is the similarity of the ratio of X-ray and bolometric luminosity for RS CVn bin-

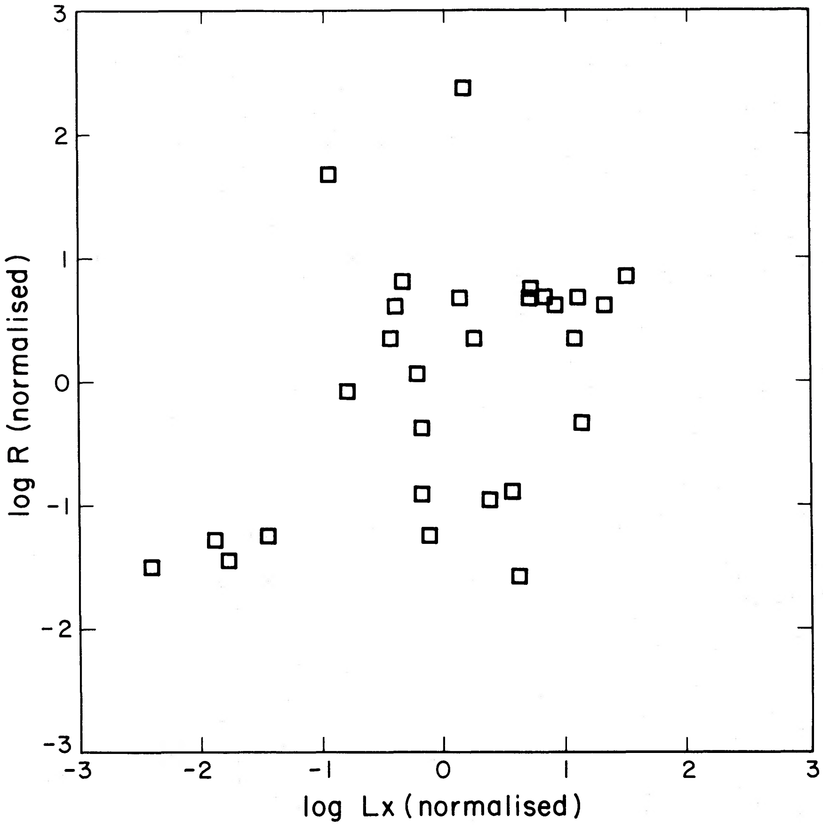

FIG. 9*a*

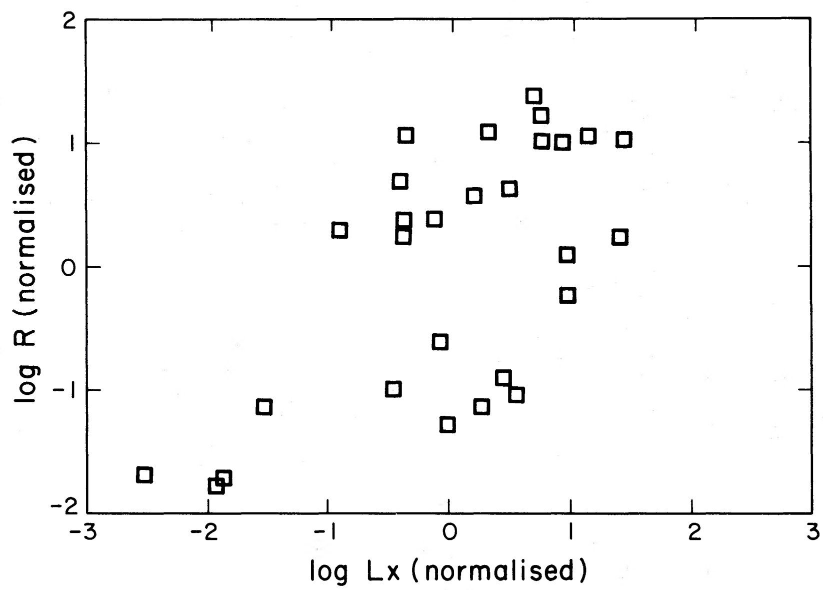

FIG. 9*b*

FIG. 9.—Radius of active component vs. X-ray luminosity in normalized variables (*a*) before and (*b*) after projection

aries and extremely late type M dwarfs, both of which are bounded from above at about 10^{-3}. Both groups of stars have surface convection zones which carry essentially all the energy flux generated in the stellar core, and we can view the energy emitted from the corona as a diversionary "tap" on this energy flux. Clearly, there must be an upper limit to the efficiency with which turbulent energy in the convection zone can be converted into (ultimately) X-ray emission through a long chain of poorly understood processes; it may be that we are seeing this upper limit of dynamo efficiency being approached in these stars.

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